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THE DIRECT BIOLOGICAL EFFECTS OF INCREASED ATMOSPHERIC CARBON DIOXIDE LEVELS

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This report assesses the likely biological nonclimatic, direct effects of carbon dioxide (CO_2) on terrestrial and aquatic ecosystems and on human health. It summarizes the current literature on the direct effects of rising CO_2 levels on the biosphere and identifies technical information needs about direct biological effects of rising CO_2 levels. The environmental and human health implications of these effects were evaluated in the context of four scenarios describing possible future carbon dioxide levels to the year 2100. The report discusses six categories of CO_2 control options: (1) increasing the rate of carbon fixation or mass transfer, (2) changing the fuel use strategy, (3) changing energy use patterns, (4) using emission source controls (5) using institutional controls to adapt society, and (6) implementing exotic strategies. No single option emerged as the best approach to controlling CO_2. The best approach will depend upon the specific problems and resources in a given region. However, because of the global nature of the problem, international cooperation will be required for truly effective control. In order to make future policy decisions regarding the problem of increasing CO_2 concentrations, we need a better understanding of the basic biological processes involved. Future research should address the direct effects of increased CO_2 levels, rather than the potential effects that may occur if and when the climate changes. Because aquatic species exhibit adverse effects at lower concentrations of CO_2 than other organisms, they should receive first priority in future investigations.

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ABSTRACT

This report presents an assessment, based on an analysis of the literature and interviews with knowledgeable scientists, of the likely nonclimatic direct effects of carbon dioxide on terrestrial and aquatic ecosystems and on human health.

The objective of this study is to provide EPA with information needed to support future decisions regarding research priorities and allocation of resources to long range environmental issues. Therefore, this study (1) summarizes the current literature on the direct effects of rising carbon dioxide levels on the biosphere, and (2) identifies technical information needs regarding the direct biological effects of rising carbon dioxide levels.

The environmental and human health implications of these effects were evaluated in the context of four scenarios describing possible future carbon dioxide levels to the year 2100.

Existing scientific knowledge regarding the direct effects of increased concentrations of CO_2 is generally limited in its coverage of species and long term effects. While many experiments have been conducted on agricultural species, effects on ornamental and woody species have not been widely studied. Moreover, experiments are generally directed to a sample of one species under limited conditions and do not consider ecosystem effects. Consequently, the existing theoretical and empirical understanding are inadequate for predicting accurately the effects of increasing concentrations of carbon dioxide. However, the potential for adverse effects is clear.

Under plausible assumptions regarding the future use of fossil fuels, CO_2 levels in the atmosphere could double to 600 ppm in the next 40 to 50 years. The direct effect on plant species may be increased growth and yields; however, the growth rates of certain sensitive species could begin to decline at higher concentrations of CO_2. Aquatic ecosystems appear to be potentially more sensitive than terrestrial communities to atmospheric carbon dioxide concentrations greater than 600 ppm. Adverse effects that could become manifest by the year 2100 include toxic effects on fish, stressful conditions for aquatic organisms that produce carbonate skeletons, and increased algal blooms in nutrient-rich areas. For human health effects, there appears to be a substantial margin of safety until at least 2100.

In order to make future policy decisions regarding the problem of increasing CO_2 concentrations, we need a better understanding of the basic biological processes involved. Future research should address the direct effects of increased carbon dioxide levels, rather than the potential effects that may occur if and when the climate changes. Because aquatic species exhibit adverse effects at lower concentrations of CO_2 than other organisms, they should receive first priority in future investigations.

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I INTRODUCTION AND SUMMARY

Background

Carbon dioxide is a colorless, odorless gas that is estimated to be approximately 0.03% (by volume) of the atmosphere. It is a natural constituent of the atmosphere and plays a key role in the growth of living organisms. The term "carbon cycle" is used to describe the chain by which carbon, in the form of carbon dioxide, is assimilated into plants by the photosynthesis process and then returned to the atmosphere through the process of decay. Animals are part of the cycle because they consume plants and excrete products that decay and release carbon dioxide. Carbon dioxide is also released by the respiratory process of animals and by combustion.

Carbon dioxide is used in carbonated beverages, refrigeration equipment, and fire extinguishers. Carbon dioxide is also used to enrich the atmosphere in greenhouses because the rate of photosynthesis depends upon the concentration of carbon dioxide.

The mean annual carbon dioxide concentration of the global atmosphere has apparently been increasing since the beginning of the industrial revolution. Current levels are approximately 330 parts per million (ppm), an increase of about 50 ppm over levels associated with the preindustrial atmosphere (Brewer, 1978a). Since systematic measurements were begun in 1958, atmospheric carbon dioxide content has increased 7%.

The major sources of the additional carbon dioxide are generally thought to be anthropogenic--largely from man's burning of fossil fuels; from deforestation and agricultural practices; and from burning nonfossilized wood and peat (see Table 1). Bolin (1970) notes that the carbon locked in coal and oil exceeds the amount of carbon in all living organisms by a factor of 50. According to the most probable models, the percentage of the cumulative production of carbon dioxide that will remain airborne 100 years from now will be between 46% and 80% (Siegnethaler and Oeschger, 1978).

Increased carbon dioxide levels are expected to have far-reaching climatic and nonclimatic effects. Carbon is the most abundant element in all known organisms, and is the basic chemical building block of life. Furthermore, carbon dioxide traps heat in the atmosphere and thereby produces the so-called "greenhouse effect." Although many scientists have been concerned about the environmental implications of enhanced carbon dioxide for several decades, only recently has there been a more widespread awareness of this issue in the United States. "Are we becoming another Venus, the runaway greenhouse?" the press now enquires.

Table 1

ESTIMATED INPUT OF CARBON DIOXIDE INTO THE ATMOSPHERE FROM ANTHROPOGENIC AND NATURAL SOURCES

(Adapted from Wong, 1978)

Source	Gross Input (10^{16} g Year^{-1})	Net Input[a] (10^{16} g Year^{-1})
Wood burning		
Fires in boreal regions	0.4	0.0
Fires in temperate regions	0.2	0.0
Tropical shifting cultivation	1.0	0.0
New tropical forest clearings	0.5	0.5
Fuel wood burning	0.2	0.006
Paper waste burning	0.08	0.0008
Soil and land		
Soil carbon loss in agriculture	0.3	0.3
Soil carbon loss on burning	0.4	0.02
Desertification	0.05	0.05
Urbanization of farmland	0.01	0.01
Fossil fuel		
Fossil fuel burning	5.0	5.0
Natural biological processes		
Respiration of land biota	63.0	0.0
Decomposition of land detritus	37.0	0.0
Respiration of ocean biota	25.0	0.0
Decomposition of ocean detritus	35.0	0.0
Total	168.1	5.9

(a) Contribution after allowance for carbon dioxide uptake for photosynthesis into plant organic matter.

Study Purpose

This report describes the findings of one of a series of exploratory studies supported by the Office of Strategic Assessment and Special Studies (OSASS). The purpose of this study is to provide OSASS with sufficient scientific information to support future decisions regarding the need for additional research on the effects of increasing atmospheric concentrations of carbon dioxide. Therefore, this study (1) summarizes the current literature on the direct effects of rising carbon dioxide levels on the biosphere, and (2) identifies technical information needs regarding the direct biological effects of rising carbon dioxide levels. Current projections indicate that the global mean atmospheric carbon dioxide concentrations will double from the present level sometime in the next century (Bacastow and Keeling, 1973; Baes et al., 1977; MacIntyre, 1980). Numerous studies have reported potential climatic effects from the carbon dioxide buildup. This report addresses the nonclimatic, direct biological effects that are likely to result from a doubling of the present atmospheric carbon dioxide levels. Potential effects on terrestrial and aquatic ecosystems, as well as on human health, are assessed in Section II. Section III defines and scopes the carbon dioxide issue in terms of public health and environmental policy implications, and presents a forecast of future environmental trends. Major information gaps and potential areas for future research are discussed in Section IV.

Methods

To identify pertinent information sources and data, SRI reviewed our internal files on carbon dioxide effects and then performed computerized literature searches on 23 data bases (Table 2). We compared these findings with results of a search on the direct effects of carbon dioxide that the Oak Ridge National Laboratory's Carbon Dioxide Information Center performed for us using their Carbon Cycles and Climate Data Base. After critically reviewing and analyzing key articles, we interviewed principal scientists currently active in investigating the direct biological effects of enhanced atmospheric carbon dioxide levels. In addition, we conducted a one-half day seminar on carbon dioxide control options (see Section III).

Summary

Terrestrial Ecosystem Effects

At least two schools of thought concerning the effects of increased carbon dioxide levels on terrestrial ecosystems have been expressed. One group is optimistic about the fertilization effect of these enhanced levels. This school stresses the well-established knowledge that carbon dioxide is essential for plant photosynthesis, and, up to certain levels, is a vital resource. For several years, carbon dioxide enrichment has been successfully used in greenhouses to increase yields and to hasten maturation of crops.

Table 2

COMPUTERIZED DATA BASES SEARCHED

Agricola, 1970-81
Aquaculture, 1970-81
Aqualine, 1974-81
Aquatic Sciences and Fisheries Abstracts, 1978-81
Biosis, 1977-81
Chem Abstracts, 1980-81
CIS (Congressional Information Service), 1970-81
Dissertation Abstracts, 1861-1981
Enviroline, 1971-81
Environmental Bibliography, 1974-81
Excepta Medica, 1974-81
Federal Index, 1976-81
Federal Register, 1977-81
IRL/Life Sciences, 1978-81
Medline, 1975-81
Monthly Catalog, 1976-81
NTIS, 1964-81
Oceanic Abstracts, 1964-81
Pollution Abstracts, 1970-81
Recon, 266 recent records
Trecs, all records
SSIE, 1978-81
Toxline, 1978-81

The other school is more cautious. Members of this group believe that we do not currently have enough information to predict the long-term effects of carbon dioxide enrichment. They stress that plant growth is the result of the interaction of many processes, any of which may limit the growth rate, and all of which are influenced by various environmental factors. For example, nutrients and light are commonly limiting factors, particularly in forest ecosystems. They also point out that controlling the yield of the economically important part of a plant is a many-faceted problem, and increased net photosynthesis does not necessarily translate into increased yield.

We reviewed the major studies on the response of vegetables, field crops, and woody species to increased atmospheric carbon dioxide concentrations. Results for greenhouse-grown vegetables and flowers have consistently shown that enhanced carbon dioxides levels up to 1,000-1,500 ppm result in increased crop yields, earlier maturation, and better quality produce for certain species. At levels greater than 2,000 ppm. photosynthesis commonly decreases and plant injury may occur. However, some plant species have been shown to respond positively to short-duration exposures at much higher levels. Most field crops have also shown increased yields, although only a few long-term studies have been conducted under field conditions. Plants that metabolize carbon dioxide by means of a three-carbon-acid pathway ("C3 plants") seem better able to utilize higher levels of carbon dioxide than those that fix carbon dioxide by a four-carbon-acid pathway ("C4 plants").

Experiments on woody species have shown that enhanced carbon dioxide levels up to 3,000 ppm have resulted in increased net photosynthesis and growth; however, almost all of the reports have concerned short-term experiments on seedlings. It is generally agreed that we do not know enough to assess the effects of increased carbon dioxide levels on entire forest ecosystems, in part because of the complexity of such systems. For example, field measurements have shown large diurnal, seasonal, and vertical natural variations in carbon dioxide levels in forests, with concentrations nearing 600 ppm just before dawn at the ground level in some plant communities. Substantial diurnal and seasonal variations in the normal carbon dioxide concentrations have also been measured in agricultural fields. A few studies have also indicated that if ambient carbon dioxide increases concurrently with concentrations of phytotoxic gases, the carbon dioxide could potentially ameliorate pollutant stress effects on photosynthesis.

Thus the evidence does not seem to support one school of though over the others. What is clear is that the further one moves from the controlled conditions of a greenhouse to the highly complex environment of a forest, the more difficult it is to assess the likely effects of increased carbon dioxide levels.

Doubling atmospheric carbon dioxide levels is expected to have little or no direct effects on fauna. Animals are more likely to be indirectly affected through their response to the changes in the plant community that may result from the increased carbon dioxide levels.

Aquatic Ecosystem Effects

The likely effects of increased levels of atmospheric carbon dioxide on aquatic ecosystems were assessed by analyzing (1) the direct toxic effects on aquatic life forms, (2) the potential nutrient effects that might stimulate primary productivity, and (3) the possible effects on water quality. Existing data indicate that a projected concentration of 0.90 mg/l in equilibrium with an atmospheric concentration of 600 ppm is not likely to have direct toxic effects on aquatic organisms. However, some fish species are apparently sensitive to and may respond to carbon dioxide levels as low as 0.88 mg/l. Carbon dioxide concentrations as low as 2.1 mg/l may have adverse effects on hatching success in certain sensitive fish species. Although levels as high as 10 mg/l are typically found in catfish-rearing ponds, long-term survival of certain fish species is know to be reduced at 12 mg/l.

An increase in atmospheric carbon dioxide from 300 to 500 ppm is likely to result in increased phytoplankton productivity only in nutrient-rich areas. These areas may respond with increased algal blooms.

Carbon dioxide affects water quality primarily by contributing to the carbonate buffer system, which, in turn, affects the pH of the water. We predict that for carbon dioxide levels of 600 ppm, the change in pH will be slight, approximately 0.03 pH units in water with an initial pH in the range of 7 to 8. These changes should be well within the tolerance ranges of almost all marine organisms.

However, a greater change is expected in water with lower pH values. The most sensitive aquatic ecosystems will probably be freshwater lakes with limited watersheds and low buffering capacities. In addition, cold water systems may be of greater concern than warm water systems, because carbon dioxide is more soluble at low temperatures.

Human Health Effects

This report reviews both the normal human physiology of carbon dioxide and adverse effects at enhanced levels. We conclude that a doubling of ambient concentrations of carbon dioxide to 600 ppm will probably have negligible human health effects. Endogenous human production of carbon dioxide generates an alveolar (deep lung) concentration of about 5% of the concentration of the atmosphere at sea level--nearly two orders of magnitude greater than 600 ppm (about

0.06%). In fact, humans are commonly exposed today to concentrations of carbon dioxide in the range of 600 ppm in both occupational and residential settings.

Adverse physiological effects have been reported in guinea pigs exposed to carbon dioxide at levels as low as 5,000 ppm. However, these effects, which were related to abnormal calcium metabolism, were reversible after an 8-week recovery period. Other studies have shown that prolonged exposure of submarine crew members to carbon dioxide at levels of 7,500-8,000 ppm may have subtle effects on calcium metabolism, but these effects have also been shown to be reversible.

Carbon Dioxide Scenarios

We summarized published forecasts of future atmospheric carbon dioxide levels in four scenarios. The scenarios were based on different assumptions concerning world energy use, fuel mixes, and carbon dioxide control strategies. If high dependence on fossil fuels is assumed, a carbon dioxide level of 600 ppm would be reached by 2020, and a level of approximately 2,400 ppm would be reached by the year 2100. At the other extreme, if control of carbon dioxide is assumed, 600 ppm would not be reached until 2050, and the carbon dioxide concentration in 2100 would be only 700 ppm. Less extreme scenarios based on assumptions of more modest energy growth rates and a gradual conversion away from fossil fuels appear more likely. SRI's best estimate is that atmospheric carbon dioxide levels may reach 600 ppm sometime between 2030 and 2040. If the world energy patterns of this century continue through the next century--a highly speculative assumption--atmospheric carbon dioxide concentrations are projected to be approximately 1,300 ppm by the year 2100.

Environmental and Human Health Implications

Under scenarios that assume moderate increases in carbon dioxide, most terrestrial biota could actually benefit from the levels expected to 2100. However, certain sensitive species, especially the C4 plants, could begin to have reduced growth rates by 2050, and possibly earlier, if fossil fuels remain the dominant energy sources.

Aquatic ecosystems appear to be potentially more sensitive than terrestrial communities to increased carbon dioxide levels. By 2100, the carbon dioxide levels could be nearly as great as or greater than the lowest levels known to cause toxic effects in certain sensitive fish species. The potential increase in the pH of the water by 2100 would probably cause stress for organisms that produce carbonate skeletons. With heavy dependence on fossil fuels, adverse effects such as a reduction in the reproductive success of certain commercial fisheries might be seen as early as 2040. Algal blooms in nutrient-rich areas might also be more common by that time.

The margin of safety for human health effects appears to be substantial. Only with the heaviest use of fossil fuels would potentially dangerous indoor carbon dioxide concentrations be reached (assuming that indoor levels are twice as great as those outdoors), and then not until 2100. A small possibility does exist that the calcium metabolism of humans could be adversely affected by chronic exposure to carbon dioxide at the levels that could conceivably be reached by 2100.

These results indicate that we should be developing both an adaptive strategy that takes advantage of the potential positive effects of enhanced carbon dioxide levels and a preventive one to help ameliorate the potential deleterious effects on aquatic ecosystems. Compared to potential effects on terrestrial and aquatic ecosystems, human health effects appear to be of little concern at the projected levels.

Control Options

The report discusses six categories of carbon dioxide control options: (1) increasing the rate of carbon fixation or mass transfer, (2) changing the fuel use strategy, (3) changing energy use patterns, (4) using emission source controls, (5) using institutional controls to adapt society, and (6) implementing exotic strategies. No single option emerged as the best approach to controlling carbon dioxide. The best approach will depend upon the specific problems and resources in a given region. However, because of the global nature of the problem, international cooperation will be required for truly effective control.

Technical Information Needs

Finally, the report concludes by identifying some of the principal research efforts currently investigating the direct biological effects of increased carbon dioxide levels and recommending priorities for future research. It is generally agreed that the considerable numbers of studies performed in the past were not designed to answer questions about long-term global carbon dioxide enrichment. Further research efforts should be preceded by the development of an analytical approach by an interdisciplinary and international team of scientists. The general consensus is that the first priority should be investigations of the direct biological effects of increased carbon dioxide levels rather than the propagative effects that may occur if and when the climate changes. Aquatic ecosystems should be emphasized in early studies because they appear more sensitive than terrestrial ecosystems and animals.

Suggested terrestrial ecosystem studies include long-term field studies of plant responses to enhanced carbon dioxide levels, breeding programs that exploit the potential benefits of increased carbon dioxide levels, and investigations of the role of the terrestrial ecosystem in global carbon cycling. Recommended aquatic ecosystems research includes toxicity studies in which sensitive life stages of aquatic biota are evaluated; investigations determining the effect of increased carbon dioxide levels on calcium-precipitating organisms; and evaluations of the potential effect of increased carbon dioxide on the species composition, succession, and productivity of phytoplankton communities. Animal and human health studies focusing on respiratory, cardiovascular, and metabolic parameters are also recommended. These should involve chronic exposures to carbon dioxide at concentrations of 600 to 2,000 ppm.

II CHARACTERIZATION OF DIRECT EFFECTS

Direct effects are defined as primary ones that result from the increasing levels of atmospheric carbon dioxide acting directly on organisms. These effects are contrasted with secondary or propagative, indirect effects that might result from eventual climatic changes. This section discusses terrestrial ecosystem effects, aquatic ecosystem effects, and effects on human health.

Terrestrial Ecosystem Effects

Background

Carbon dioxide is essential for photosynthesis and plant growth, and thus, up to certain levels, it is a vital resource. Various researchers have shown linear increases in carbon dioxide uptake by agronomic and horticultural species as atmospheric carbon dioxide levels increase from 300 to 600 ppm. Levels up to 1,000 ppm generally have been found to be beneficial for plant growth, although they have not necessarily produced linear increases (Ghoddousi, 1970; Allen, 1979; Hicklenton and Jolliffee, 1980). Depending on other environmental factors, especially light availability, and the plant species involved, further increases in carbon dioxide levels up to 2,000 ppm have also resulted in additional stimulation of photosynthesis and growth. The optimal concentration for commercially grown greenhouse crops appears to be 1,000-1,500 ppm (Strain, 1978). At levels greater than 2,000 ppm, photosynthesis commonly decreases and plant injuries, including yellowing and leaf necrosis, may occur (Gerakis, 1974). However, there have been a few reports of crops tolerating much higher carbon dioxide levels, at least for short durations (see Wittwer and Robb, 1964).

Natural Levels in Ecosystems. It is well-documented that variations in the concentration of carbon dioxide are greatest near the surface of the earth as a result of assimilation and respiration of vegetation and soils, the burning of fossil fuels, and exchanges with the sea (Kelley, 1969; Garrett et al., 1978). Carbon dioxide concentrations in the air near rapidly growing vegetated surfaces vary greatly throughout the day and season, mainly due to the absorption or release of carbon dioxide by crop plants (Inoue, 1974). At higher altitudes these variations are greatly decreased.

Natural variations in carbon dioxide levels have been measured for various forest and crop fields. Allen et al. (1972) cite a study of a Nigerian tropical rain forest where at heights between 0.3 and 1.2 meters (m), carbon dioxide concentrations ranged between 330 to 580 ppm. In a Costa Rican forest, Allen et al. (1972) found carbon dioxide concentrations to vary over a single 24-hour period from 260 to 330 ppm at 10 m from the ground. They identified three carbon dioxide source layers (ground level, trunk space, and above the tree canopy) and two sink layers (top canopy and bottom canopy). Similar sources and sinks were identified by Garrett et al. (1978) in an oak-hickory forest in Missouri. Here the seasonal mean daytime concentrations varied from about 310 to 350 ppm. As much as a 100 ppm difference in the carbon dioxide concentration was noted between the early morning and the late afternoon reading at a given height in the forest after an unusually warm day with little wind. Similar data taken at 2 m in a cornfield in New York have shown carbon dioxide levels varying from 270 to 450 ppm over a 24-hour period (Allen et al., 1972).

In natural systems, concentrations of carbon dioxide as high as 13% have been recorded in the soil atmosphere of a forest (Voight, 1962 as quoted by Phares, 1980). Phares (1980) notes that most forest stands are already enriched to some extent with carbon dioxide from the soil atmosphere. Because carbon dioxide is released continuously from the soil and because the air mass below the canopy of a closed forest stand usually has little turbulence, especially at night, a gradient develops in a closed forest stand--high concentrations are found at the soil surface and lower ones in the upper portions of the canopy (Phares, 1980).

C3 versus C4 Plants. Two common types of plants ("C3" and "C4") have different responses to carbon dioxide concentration changes. These plant groups differ biochemically and morphologically in several ways, the principal differences being the chemical manner in which the plants fix carbon dioxide (Downton, 1971; Noggle and Fritz, 1976). The C4 plants contain enzymes for a series of reactions that form four carbon acids as the first products of carbon dioxide assimilation. C4 plants (e.g., corn, sorghum, sugarcane) are often described as photosynthetically more efficient because of their very low rates of photorespiration (respiration in the light). They burn up less carbon during the day, and thus have a greater amount available for growth.*

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* Plants not only take up carbon dioxide to produce organic compounds and the important by-product, oxygen, they also respire--that is, use oxygen to oxidize sugars and other compounds to carbon dioxide and water. To gauge productivity, it is necessary to measure net photosynthesis, the difference between the amount of carbon dioxide assimilated and that lost in respiration. Dark respiration does not require light and is a major source of essential energy for plants. Photorespiration is light-dependent and appears to provide little useful energy (Marx, 1973). However, Yamachi and Yamada (1980) have pointed out that one of the roles of photorespiration is probably the maintenance of the carbon transport system in C3 plants.

Most C4 species have a much higher carbon dioxide exchange rate at high light. Their stomates also require greater light intensity to open, and they perform best under high light and warm conditions, whereas C3 species (e.g., wheat, alfalfa, soybeans) do best under cooler conditions (Lemon, 1977). The advantages of C4 photosynthesis over C3 photosynthesis have been shown to be greatest under conditions of high light intensities, high temperatures, and limited water supply; such climatic conditions are prevalent in many deserts and grasslands, the regions of the world where C4 plants commonly occur. According to Ehlringer and Bjorkman (1977), under conditions of sufficient soil mosture, a C3 plant will actually have a greater potential for carbon gain at low temperatures whereas a C4 plant will have a greater potential at high temperatures. The crossover point is approximately 25 to 30°C.

One difference is particularly relevant to this study. C4 plants evidently close their stomata in response to increases in carbon dioxide concentration to a greater extent than C3 plants do. For example, C3 plants such as sugarbeet, alfalfa, and tomato have shown linear responses to carbon dioxide enhancement from 300 to 2,000 ppm, whereas corn, a C4 plant, has shown curvilinear responses up to 600 ppm (Lemon, 1977). In another study, the stomata of corn closed at concentrations greater than 400 ppm at a rate proportional to the increase in the level of carbon dioxide. This closure behavior tended to counterbalance the effects of increasing carbon dioxide in the ambient air (Gifford, 1970, as reported in Allen, 1979).

Thus weighing the advantages and disadvantages of C4 plants is not a simple matter. Lemon (1977) points out that even though C4 plant species begin at the basic photochemical level at a two- to threefold advantage over the C3 group (because the C4 carboxylation enzyme has a two- to threefold affinity for carbon dioxide), this advantage is eliminated at the short-term growth level by the buffering effect of increasing levels of organization in a plant.

Van Keulen et al. (1980) emphasize that the crucial factor is the plant's stomatal behavior which may be different for different species or under different environmental conditions. If carbon dioxide-induced stomatal regulation is present, the direct result of increased carbon dioxide concentration will be lower daily rates of water loss, rather than higher daily rates of production. However, under conditions that make water the main limiting growth factor, this phenomenon may lead indirectly to higher production levels over the season because the available moisture is used more efficiently. Indeed, many C4 plants, as noted previously, appear to have evolved in the more arid regions of the world.

In a study of two adjacent, native, cool-desert communities, Caldwell (1974) found that the C3 dominated shrub community (the

Ceratoides lanata community) exhibited greater maximal leaf carbon dioxide fixation rates, but that the C4 dominated shrub community (the Atriplex confertifolia community) exhibited greater annual carbon fixation, standing biomass, and productivity. However, the higher productivity of the C4-dominated community is not necessarily linked to the C4 photosynthetic pathway, according to Caldwell. Nobel (1980) attributed the success of Hilaria rigida, a hardy C4 grass in the Mojave and Sonoran deserts, to the fact that its major stomatal openings occurred in the relatively cool winter-spring months.

If carbon dioxide-induced stomatal regulation is absent, plants may benefit from higher carbon dioxide levels through increased assimilation rates, as has been commonly observed in C3 plants grown in greenhouses (e.g., tomatoes and cucumbers). However, these rates can only be maintained when the moisture supply can be held at near-optimal levels, and this is an inefficient use of water.

Previous Studies. Certainly the study of the relationship of plant growth to atmospheric carbon dioxide is among the oldest in modern science, dating back from the early experiments by Priestly and Igen-Houz in the 1700s (Baker and Lambert, 1980). By the early 1900s, review articles discussing these early experiments began to appear, e.g., Brown and Escombe (1902). By the 1920s, mimeographs and books had been published in northern Europe on the carbon dioxide fertilization of glasshouse-grown vegetables (Wittwer and Robb, 1964). More recently, several extensive reviews of carbon dioxide effects on plants have been prepared (e.g., Wittwer and Robb, 1964; Wittwer, 1967 1980a; Lemon, 1977; Strain, 1978, 1981; and Allen, 1979.

In April 1979, the American Association for the Advancement of Science (AAAS) conducted a workshop at Annapolis, Maryland, called "Environmental and Societal Consequences of a Possible CO_2-Induced Climatic Change." The workshop, sponsored by the U.S. Department of Energy in connection with its National Program on Carbon Dioxide, Environment, and Society, was attended by 85 experts from the physical, biological, and social sciences. Although the emphasis of the workshop was on climatic impacts, biological effects of enhanced atmospheric carbon dioxide levels were also discussed in several of the panels.

Note, however, that although numerous studies of carbon dioxide effects on plants have been conducted, most of them have been fairly short in duration. Many have been carried out under conditions quite dissimilar to field conditions. For example, a large number of studies report leaf chamber measurements from a single leaf on a single plant in a single environment at a single point in time (Lemon, 1977). An increasing number of studies now employ field chambers.

Potential Impacts

A doubling of global carbon dioxide concentrations may affect plants in several ways. The major anticipated changes are listed in Table 3.

Two Schools of Thought

Given the complexity inherent in plant response to enhanced carbon dioxide levels and differences in the objectives of various groups involved in the management of our biological resources, it is not surprising to find that we have at least two schools of thought concerning the likely effects of enhanced levels of carbon dioxide on the terrestrial ecosystems of the world. Some scientists, particularly those who work closely with managed ecosystems, are optimistic about the fertilization effect of increasing carbon dioxide levels (Wittwer, 1980a, 1980b; Panel III of AAAS, 1980). They point out that only 5-10% of the dry weight of plants comes from minerals and fertilizers; the other 90-95% comes from airborne carbon dioxide. They also point out that photosynthetic processes usually operate at less than optimal levels in normal atmospheric carbon dioxide concentrations of 300 ppm (Funsch et al., 1970), and that greater concentrations are likely to increase photosynthetic efficiency, reduce water requirements, accelerate growth, and increase productivity. Indeed, more than 15 years ago, Loomis and Williams (1963) listed carbon dioxide supply, along with light availability and leaf area, as major limiting factors to the attainment of upper limits of crop productivity. Similarly, Bonner (1962) stated that considering crops grown under optimal temperature, nutrient, and water conditions, and free from pest limits are generally limited, at high light densities, by the carbon dioxide concentrations of the air.

The optimistic school of thought suggests that increased carbon dioxide levels may stabilize yields and decrease the year to year variability due to weather (Kanemasu, 1980). It remains highly uncertain, however, whether carbon dioxide fertilization will fully offset the reduced growth and productivity that might come about with carbon dioxide induced climatic changes.

The other school of thought, generally held by those who are more closely associated with natural, less-managed ecosystems, but also shared by some agronomists, holds that we do not currently have enough information to predict long-term impacts of carbon dioxide enrichment (see Strain, 1981). They point out that plant growth is the result of the complex interaction of many processes, any of which may limit the growth rate and all of which are influenced by various environmental factors (Hofstra and Hesketh, 1975). Similarly, Lemon (1977) notes that both plant processes and the climate process are coupled in ways much more complex than originally realized, and that little is known about the effects of carbon dioxide enrichment on natural systems.

Table 3

POTENTIAL CHANGES IN VEGETATION FROM A DOUBLING OF GLOBAL CARBON DIOXIDE CONCENTRATIONS

- Net photosynthesis, photosynthate composition, and allocation; dark carbon dioxide fixation rate; amount of biomass produced
- Photorespiration and dark respiration
- Growth rate, maturation, senescence
- Reproductive behavior; pollination; amount and quality of flowers, fruits, and seeds produced; germination of seeds and spores; phenology
- Transpiration; stomatal conductance; water use efficiency
- Growth form; leaf area, leaf structure; canopy shape; root/shoot ratio
- Atmospheric pollution tolerances
- Ecological interactions, e.g., herbivory, predator-prey relations; intra- and interspecific composition, species composition; nitrogen fixation capability; decomposition

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Source: Based on Strain, 1978 and 1981; AAAS, 1980.

Photosynthesis is only one component of plant behavior. Several other aspects of plant behavior also respond to atmospheric carbon dioxide concentrations, e.g., vegetative and reproductive growth, product biosynthesis, and population and ecosystem interactions. They emphasize that increased photosynthesis does not necessarily lead to increased economic yields. Even the number of flowers produced is not necessarily correlated with grain yield, e.g., in soybeans (see Maddox, 1974). Yield (i.e., marketable produce) is indeed a many-faceted phenomenon influenced by factors other than photosynthesis alone. Even a seeming yield increase may simply be a result of more water in the leaves, as has been shown for certain greenhouse lettuce-growing operations under enhanced carbon dioxide levels (Lemon, 1977). Similarly, Smith (1980), referring to natural ecosystems, states that although a doubling of carbon dioxide levels may cause photosynthetic rates to increase by about 20%, it is impossible, on the basis of existing information, to predict whether net changes will occur in the overall carbon pool.

This school of thought indicates that too much optimism about the beneficial effects of increased carbon dioxide in the atmosphere seems unwarranted, because under natural conditions the nutrient supply is commonly the major factor limiting primary production (Van Keulen et al., 1980). Lemon (1977) contends that the same factors that reduce the C4 advantage in photosynthesis would reduce those of carbon dioxide enhancement. He concludes that:

- Environmental constraints will limit plant growth
- The final yield (carbon accumulation) of a plant community is governed by so may other plant processes in addition to photosynthesis that advantages to this single process are muted
- The life cycle of plant systems tends to be shortened with either greater photosynthesis in single plants or faster growth of forests such that net carbon gain in the end is nil.

Plant Response Data

Appendix A tabulates some of the major data that have been obtained on the responses of vegetables, field crops, and woody species to elevated levels of atmospheric carbon dioxide. Results for greenhouse-grown vegetables and flowers quite conclusively show that increased carbon dioxide levels increase crop yields and speed maturation, particularly in tomatoes and lettuce. Supplementary carbon dioxide in greenhouse culture is also known to enhance the quality of certain species (Duncan and Barfield, 1970). It is not surprising that carbon dioxide enrichment techniques are commonly used in commercial greenhouses (see Smith, 1977; Wittwer and Robb, 1964; Wittwer, 1967). Calvert and Slack (1975) recommend the maintenance of a three-fold enrichment level throughout the entire enrichment period (pre and post planting) for the most cost-effective production.

Most of the field crop investigations have also shown increases in net primary productivity with enhanced carbon dioxide levels up to 1,000 ppm. The effect, like those of other environmental factors, is often dependent on the developmental stage of the plant. For example, wheat yields in northwest Mexico have been shown to be particularly sensitive to environmental factors (light, carbon dioxide) 60 to 90 days after sowing (Fischer et al., 1981). Enhanced levels of atmospheric carbon dioxide have also been shown to reduce top/root ratios and enhance tuber growth. Wittwer (1980a) notes that this characteristic may be particularly beneficial for increasing drought resistance and for yields of certain root and tuber crops. Indeed, potato plants have been shown to be particularly well-suited to carbon dioxide enrichment.

Only one study, a short-term laboratory investigation, has shown that a C3 plant was negatively affected by an elevated carbon dioxide level. Raper and Peedin (1978) grew two cultivars of tobacco at two nitrate levels and at two carbon dioxide levels, 400 and 1,000 ppm. The net carbon dioxide exchange rates were greater at 400 than at 1,000 ppm for both cultivars at both nitrate levels. The authors state that these findings are not necessarily in conflict with observations of absolute increases in yields in carbon dioxide-enriched atmospheres that have been observed for other species. The tobacco plants were in a vegetative condition and did not possess the dominant photosynthate sink of reproductive growth. According to Raper and Peedin, the explanation of the lower photosynthetic rates may be related to excessive accumulation of starch or to changes in stomatal conductance.

Assessments of the effects of elevated carbon dioxide levels on C4 plants have led to mixed results. For example, in certain experiments, net assimilation rates have increased up to 3,300 ppm, but in others, dry matter production was decreased at levels exceeding 600 to 800 ppm. The differences may be related to the length of the experiment and to environmental factors associated with the experimental conditions. In general, however, high carbon dioxide concentration rates are known to promote faster growth in C3 species than in C4 species. C3 plants evidently have a better potential for responding to increased carbon dioxide than C4 plants because the stomata of the leaves of C3 plants do not close as readily as carbon dioxide concentrations increase.

It has been suggested that atmospheric carbon dioxide enrichment will probably make weeds with C3 photosynthetic pathways more competitive with crops having the C4 pathway and weeds with the C4 pathway may become less competitive with crops having the C3 pathway (Patterson and Flint, 1980).

Most of the experiments conducted on woody plants over short time periods have been on seedlings. We were not able to find any studies on the entire life cycles of trees other than a computer simulation model. Enhanced carbon dioxide levels up to 3,000 ppm have resulted in increased net photosynthesis and increased growth of seedlings. Young trees appear to make short-term dry matter gains in response to added carbon dioxide in growth chambers. Linear relationships have commonly been found between carbon dioxide levels and photosynthesis of woody species up to about 500 ppm. But as Lemon (1977) points out, intermittent or short-term responses may have little bearing on final outcome, and seedlings are surely not representative of trees at other stages of maturity.

The few field studies that have been conducted on woody species have also shown increased levels of net photosynthesis with enhanced levels of carbon dioxide (up to 935 ppm). However, it is generally agreed that our state of knowledge does not permit us to assess the full consequences of enhanced carbon dioxide levels on forest productivity. This is unfortunate because even though dense forests cover only about 30% of the land surface, about 90% of the living biomass is found there (Bolin, 1977). According to Phares, (1980), essentially no work has been conducted on assessing the response of an entire forest stand to carbon dioxide enrichment. One can speculate that limitations in moisture and nutrients would largely buffer the potential effect of carbon dioxide enrichment on forest productivity. The AAAS panel on environmental effects of enhanced carbon dioxide levels on the less managed biosphere concluded that estimates suggest a doubling of carbon dioxide levels will cause photosynthetic rates to increase by about 20% (AAAS, 1980). However, the panelists found it impossible to predict whether net changes will occur in the overall carbon pool.

A computer model of a forest ecosystem, which was developed by Botkin et al. (1973) to simulate long-term effects of carbon dioxide increases on a natural temperate forest ecosystem, predicted that carbon dioxide fertilization would favor shade-tolerant, long-lived species and hasten succession so that the climax plant community is reached sooner. The standing crop also increased 40% when carbon dioxide was increased by 100%. (The modelers had made the simple assumption that a percentage increase in carbon dioxide would yield an equal percentage increase in the yearly increment of each tree.) The authors speculate that the sole effects of more carbon dioxide might be to compress the time scale of development without any change in the final yield of the forest. They also point out that a managed monoculture could give entirely different results.

Lemon (1977) points out that even a rather small increase in overall photosynthetic rate due to carbon dioxide might have a significant buffering effect on the anticipated increases in atmospheric carbon dioxide if the living biomass and soil humus pools are large and pool sizes are not decreasing. Estimates of the size of the terrestrial dead organic matter pool, largely made up of organic carbon in the soil and peat, vary considerably, but it may equal or exceed the living biomass on land. Lemon (1977) indicates that there is reason to believe that intensive agriculture, if wisely managed, can actually maintain or increase soil humus instead of depleting it. Some evidence even indicates that despite the cutting of forests and agricultural activities, the overall terrestrial biosphere activity in the northern hemisphere may not have changed at all recently. Lemon (1977) cites the observations of Hall et al. (1975) that the annual highs (representing winter net respiration) have equalled the annual lows (summer net photosynthesis) over the 15 year record of the Mauna Loa, Hawaii, carbon dioxide samplings (1958-1972). Because the year-to-year difference between each high and the following low has not changed over the years, the evidence does not indicate a reduction in net photosynthesis in the northern hemisphere. However, as the authors note, the data are subject to other interpretations.

Effects on Other Native Plant Species. We found one study concerning the effects of enhanced carbon dioxide levels on a series of native plants from a given plant community. Wright (1974) published regression equations based on a laboratory study of photosynthesis for 22 species native to the San Bernardino Mountains as a function of carbon dioxide concentration over the range of 280 to 480 ppm. (Wright also included two crop species.) These data showed substantial increases for all of the plants tested in net photosynthesis with enhanced carbon dioxide levels.

The few studies we found on carbon dioxide effects on nonflowering plants indicate that these plants can tolerate high levels of this gas. Fern (*Onoclea sensibilis*) spores germinated in atmospheres enriched to 2% (20,000 ppm) carbon dioxide. However, higher levels were progressively more inhibitory (Edwards, 1977). A forest population of a moss (*Polytrichum juniperinum*) showed greater photosynthetic responses to increased carbon dioxide concentration than did an alpine population (Bazzaz et al., 1970). The growth of a fungus that grows along wheat roots (*Ophiobolus gramini*) was not increased by the removal of carbon dioxide (Ferraz, 1974). The author concludes that the fungus can tolerate fairly high levels of carbon dioxide and that the bicarbonate ion, rather than the undissociated carbon dioxide, acts as a growth depressor. High atmospheric concentrations of carbon dioxide (10 to 20%) are known to extend the storage life of meat by inhibiting respiration and growth of meat storage bacteria (Gill and Tan, 1980) but only at levels a thousand times greater than those considered in this study.

Interactions with Pollutants. A limited number of studies have been conducted to determine the effects of large concentrations of carbon dioxide accompanied by other pollutants. The results indicate that if ambient carbon dioxide increases concurrently with phytotoxic gases (e.g., ozone, nitrogen, and sulfur oxides), the carbon dioxide could potentially ameliorate pollutant stress effects on photosynthesis. Coyne and Bingham (1977) measured ambient carbon dioxide concentrations in the San Bernardino Mountains of Southern California and found that they fluctuated directly with the level of air pollution and are generally highest (380 ppm, compared with a background level of 320 ppm) when ozone levels are highest. Green and Wright (1977) investigated the response of ponderosa pine in the San Bernardino Mountains to enhanced carbon dioxide levels. They found that net photosynthesis of ponderosa in the field responded in a linear fashion to carbon dioxide enhancement up to levels of 450 to 500 ppm. Severe damage from oxidant air pollution reduced but did not eliminate the response to carbon dioxide enhancement. Hou et al. (1977) exposed alfalfa plants to high sulfur dioxide and nitrogen dioxide concentrations at two carbon dioxide concentrations: ambient (315 ppm) and high (645 ppm). The high carbon dioxide concentration was found both to increase carbon dioxide uptake by the plants and to protect them from adverse effects of sulfur dioxide and nitrogen dioxide.

Effects on Animals

A doubling of atmospheric carbon dioxide levels is expected to have little or no direct effect on animals. Animals are more likely to be affected indirectly through their responses to the changes in plant communities that may result from increased atmospheric carbon dioxide levels.

Short exposures of less than 2 minutes to pure carbon dioxide have been successfully used for the narcotization of honey bees. Such exposures did not alter the orientation and successful return of released forager honey bees to the colonies (Ebadi et al., 1980). A concentration of 60% carbon dioxide maintained for 4 days is required to kill all stages of most insects found in stored products. Treatment of successive generations of granary weevil adults with carbon dioxide produced insects with a threefold increase in the tolerance to the gas in seven generations (Bond and Buckland, 1978 and 1979). In a study of acute mortality of silkwork larvae, Takizawa and Itzuka (1975) found no deaths at 1.4% (14,000 ppm). At 2.6% (26,000 ppm), mortality rates increased with each instar.

The only study we have found on the effects of enhanced carbon dioxide levels in birds was one in which broiler chickens were exposed to 3,000, 6,000, and 12,000 ppm of carbon dioxide for the 4 week brooding period (Reece and Lott, 1980). Their performance was compared to that of controls exposed during brooding to atmospheres in which the carbon dioxide level did not exceed 1,000 ppm. Exposure at 3,000 and 6,000 ppm did not significantly affect body weights at 4 or 7 weeks, but exposure at 12,000 ppm depressed body weights at 4 weeks by about 60 grams (g). The weight deficiency persisted until 7 weeks of age.

We found only one study of effects on mammals. It compared the survival time of wild rabbits exposed at very high concentrations (30-60%) of carbon dioxide to that of domesticated rabbits (Hayward and Lisson, 1978). The survival time of wild rabbits exposed to elevated concentrations of carbon dioxide was more than twice as long as that of the domestic strain. For wild rabbits, constant levels of carbon dioxide greater than 30% are required for lethality. These findings support the hypothesis that fossorial mammals have adapted physiologically to high carbon dioxide concentrations encountered in their burrows.

Aquatic Ecosystem Effects

Background

Atmospheric carbon dioxide is in a dynamic equilibrium with the carbonate buffer system in water. The equations that characterize this system are:

$$H_2O + CO_2 \rightleftarrows H_2CO_3$$

$$H_2CO_3 \rightleftarrows H^+ + HCO_3^-$$

$$HCO_3^- \rightleftarrows H^+ + CO_3^=$$

The amount of carbon dioxide present in pure water in equilibrium with the atmosphere is determined by the partial pressure of carbon dioxide in the atmosphere and the Henry's Law constant for the desired temperature. For an atmospheric carbon dioxide concentration of 330 ppm and a water temperature of 25°C, the solubility of carbon dioxide in milligrams per liter (mg/l) is given by:

$$330 \times 10^{-6} \text{ atm} \times 0.034 \text{ moles/l/atm} \times 44 \text{ g/mole} = 0.48 \text{ mg/l}.$$

At an atmospheric concentration of 600 ppm, aqueous carbon dioxide would be in equilibrium at 0.90 mg/l at 25°C. The effect of temperature on the solubility of carbon dioxide is shown in Table 4.

Other factors that influence the level of free carbon dioxide in aqueous environments include pH, the presence of various salts, and biotic factors such as algae and bacteria.

Carbon dioxide in natural environments is rarely uniform in distribution or in equilibrium with the atmospheric levels. Decomposition of organic material in sediments can result in supersaturation of overlying waters with carbon dioxide. Levels as high as 5.5 mg/l (Parks, 1975), 10 mg/l (Boyd et al., 1979), 161 ppm

Table 4

SOLUBILITY OF CARBON DIOXIDE IN PURE WATER AT DIFFERENT TEMPERATURES

°C	mg/l
0	1.10
1	1.06
2	1.02
3	0.99
4	0.94
5	0.91
10	0.76
15	0.65
20	0.56
25	0.48
30	0.42

Source: Boyd, 1978.

(Mandal and Hakim, 1975), and 210 ppm (Crawford, 1979) have been reported from fish culture ponds. McKee and Wolf (1963) report that 5% of natural waters that support good fish populations contain less than 0.1 mg/l carbon dioxide, 50% contain less than 1.5 mg/l carbon dioxide, and 95% of such waters contain between 1.5 and 15 mg/l carbon dioxide. These data are in agreement with those of Kempe (1979), who concludes that the partial pressure of carbon dioxide in ground and river waters is approximately 10 times that of atmospheric carbon dioxide. This phenomenon results in part from the high levels of carbon dioxide typically found in ground waters in contact with carbonate rock. Such waters retain their high carbon dioxide levels for some time after leaving contact with the rock by way of natural springs.

Similarly, bodies of water, or portions thereof, may be undersaturated with respect to atmospheric carbon dioxide levels. Algal blooms have marked effects on the rate of carbon dioxide exchange between air and water and remove carbon dioxide faster than it can be replenished (Koyama et al., 1977; Boyd, 1973). The result is a transient decrease in free carbon dioxide concentration and a consequent increase in pH. The effects of phytoplankton blooms and decomposition also interact, as shown by Benndorf (1980), who reported that carbon dioxide levels varied seasonally between 0.00 and 13.72 mg/l in an eutrophic reservoir. On a much larger scale, different water masses in the oceans come into less contact with the atmosphere and remain undersaturated with respect to carbon dioxide (Brewer, 1978b; Dahlman et al, 1980). Consequently, oceans in the higher latitudes act as a sink for atmospheric carbon dioxide, whereas those in the lower latitudes are a source of carbon dioxide.

The following discussion of potential effects of increased levels for atmospheric carbon dioxide in aquatic ecosystems is broken down into three areas. These are (1) direct toxic effects on aquatic life forms, (2) potential of additional carbon dioxide to act as a nutrient source and stimulate primary productivity, and (3) effects on water quality. In general, the data have been converted to mg/l to facilitate comparisons. The conversions were made using Henry's Law constant for 25^{o}C. This is not a precise conversion in view of existing differences in water qualities and temperatures, but it is a good approximation.

Toxicity Effects

Existing data indicate that a projected concentration of 0.90 mg/l in equilibrium with an atmospheric concentration of 600 ppm is not likely to have direct toxic effects on aquatic organisms. Concentrations of carbon dioxide that have been shown to produce effects in aquatic organisms are shown in Table 5. In general, most of the levels that produce detectable effects are substantially higher than concentrations that would presumably result from an increase in atmospheric carbon dioxide to 600 ppm. The toxic effect levels are also higher than the supersaturated levels of carbon dioxide currently seen in many aquatic systems. Some exceptions to this observation should be noted. Kelly (1946) as cited in Brownell (1980) reported that carbon dioxide concentrations as low as 2.1 mg/l retarded the development and reduced the hatching success of Pacific herring eggs. However, pH and exposure concentrations were not well controlled in this study. Nonetheless, the possibility of effects at concentrations as low as 2 mg/l exists in this species. Bylko (1980) found marked species-dependent differences in sensitivities to carbon dioxide levels in the concentration range of 4.7-35.4 mg/l. In some species embryo survival and development were enhanced by concentrations as high as 35.4 mg/l, whereas delterious effects were found on embryos of other species at levels as low as 4.7 mg/l. Similarly, changes in blood chemistry have been found in coho salmon at concentrations as low as 6.16 mg/l (Bubien and Meade, 1979), and reductions in respiratory efficiency were shown in dogfish maintained at low dissolved oxygen levels with 2.3 mg/l carbon dioxide. Finally, the low sensory threshold for carbon dioxide (as low as 0.88 mg/l) in some fish species (McKee and Wolfe, 1963; Yoshii et al., 1980) suggests that fish are sensitive to and respond to relatively low levels of carbon dioxide.

The free carbon dioxide concentration also affects the carbon dioxide tension in the gills and blood. As a result, transfer rates of chemical toxicants may be modified (Broderius et al., 1977; Ray, 1978). This same effect also results in reduced efficiency in oxygen utilization. As a consequence, the toxicity of carbon dioxide is enhanced at low (less than 3-5 mg/l) dissolved oxygen levels (McKee and Wolf, 1963).

Potential toxic effects on aquatic plants appear limited. Revelle et al. (1980) stated that phytoplankton photosynthesis occurs largely by the C3 pathway. This pathway is very sensitive to ambient carbon dioxide levels, and Revelle states that alterations in species composition could occur as a result of changes in carbon dioxide levels. Other investigators have questioned the effect of increased carbon dioxide levels on organisms that precipitate calcium for use in exo-skeletons. A study by Smith and Roth (1979) on the rate of calcification in marine coral exposed to several concentrations of carbon dioxide suggests that this will not be a problem at the levels we are considering, although data on a variety of species are lacking.

Table 5

CARBON DIOXIDE LEVELS CAUSING DELETERIOUS EFFECTS ON AQUATIC ORGANISMS

Carbon Dioxide Concentration--mg/l[(a)]	Effect	Reference
TURTLE		
10 o/o[(b)]	In air, increased the respiratory frequency of turtles	Milsom and Jones, 1979
FISH		
0.88 (2×10^{-5}M)	Sensory threshold for eel	Yoshii et al., 1980
1-6	Fish sense and avoid	McKee and Wolfe, 1963
1.7-22.0	Levels did not enhance effect of oxygen and nitrogen supersaturation on juvenile sockeye salmon	Nebeker et al., 1976
1.7-25.9	No effect on feeding or survival of cape sole larvae during 24-hour exposure	Brownell, 1980
2.1-18.5	Reduced hatching and retarded development of Pacific herring eggs, but pH and exposure concentrations not well controlled	Kelly, 1946 (in Brownell, 1980)
2.30 (1.02 mmHg)	Reduced ability to use oxygen increased ventilatory rate at 160 mmHg partial pressure of oxygen in dogfish	Truchot, et al., 1980
4.7-19.0	Impaired embryo development in three species of fish that produce pelagic (free-floating) eggs	Bylko, 1980
4.7-35.4	Increased embryo survival in four species of fish that produce eggs that attach to plants during the developmental stages	Bylko, 1980

Table 5 (Continued)

Carbon Dioxide Concentration--mg/l[(a)]	Effect	Reference
5.23-5.74	Increased mortality of roach, bream, blue bream, and white bream embryos	Romanenko, 1981
5.53-6.16 (2.46-2.74 mmHg)	The partial pressure of carbon dioxide in blood of juvenile coho salmon changed 2.33 mm; blood pH changed 0.14 units; lack of compensatory mechanism could indicate possible long-term effects; juvenile coho salmon was the test species	Bubien and Meade, 1979
10	Typically found in catfish rearing ponds	Boyd et al., 1979
More than 10	Trout develop nephrocalcinosis; could impair smolting ability	Smart, 1980
12	Long-term fish survival reduced	McKee and Wolfe, 1963
12-55	Produced nephrocalcinosis (calcium deposits in the kidney) in rainbow trout exposed for 275 days	Smart, et al., 1979
14-21.3	Cessation of growth in sturgeon fingerlings	Romanenko, 1981
17.6 and 35.2 (0.4 and 0.8 mmol/l)	Induced changes in activity of respiratory enzymes in the gill and liver of carp	Romanenko et al., 1979 (also Arsan, 1980 and Solomatina, 1980)
20	Harmful to rainbow trout at pH 5.5; low pH values enhance toxicity of free CO_2	Albrech, 1977
28	No effect on mass of newly hatched rainbow trout fry after exposure during incubation	Douderoff and Shumway, 1970 (in Brownell, 1980)

Table 5 (Continued)

Carbon Dioxide Concentration--mg/l[a]	Effect	Reference
40	Withstood by fish if dissolved oxygen levels do not limit respiration	Boyd et al., 1979
45	Lethal limit for trout	McKee and Wolfe, 1963
48.4 (1.1 mmol/l)	Marked change in blood pH, blood potassium and sodium levels and bone calcium and magnesium content in carp	Romanenko, et al, 1978
48.4 (1.1 mmol/l)	Maximum tolerable concentration for carp at 17-18°C	Romanenko, 1981
55	General limit for freshwater fish; some stress and effect on growth	Smart, 1980
55-78.5	Interfere with ability of trout eggs to hatch	McKee and Wolfe, 1963
79-90 (35-40mmHg)pCO_2	Produced nephrocalcinosis and changes in blood pH of rainbow trout	Eddy et al., 1979
less than or equal to 125	No effect on hatching of chum salmon eggs	McKee and Wolfe, 196
226.48 (100.66 mmHg)(c)	Increased pCO_2 (partial pressure of carbon dioxide) in carp blood 3X; increased blood glucose and reduced blood pH markedly	Smit and Hattingh, 1978
________(d)	Narcosis (a state of stupor) occurred in carp exposed to carbon dioxide levels associated with pH of 4.6; recovery occurred at pH of 4.9	Mitsuda, et al., 1980

Table 5 (Concluded)

Carbon Dioxide Concentration--mg/1[a]	Effect	Reference
FUNGI		
138 (70 mmHg)	Concentration in air over water inhibited sporulation of 12 species of aero-aquatic fungi	Fisher and Webster, 1978
138 (70 mmHg)	30% reduction in growth of 4 species of aero-aquatic fungi; concentration in air over water	Fisher and Webster, 1979
CORALLINE ALGAE		
0.06 and more than 33.8 (0.04 and more than 2.26 o/o in air)	Bubbled through media; reduced calcification in red coralline algae	Smith and Roth, 1979
1.6-15.7 (0.11-1.05 o/o in air)	Bubbled through media; increased calcification in coralline red algae	Smith and Roth, 1979

(a) If the authors did not state the carbon dioxide concentration in milligrams/liter, the original units are given in parentheses.

(b) Unit is the air concentration, not bubbled through water and thus not converted to milligrams/liter. The level is approximately equivalent to 33 ppm.

(c) Millimeters of mercury.

(d) The actual carbon dioxide concentration was not given. See notes under the "Effect" column.

Nutrient Effects

Levels of carbon dioxide associated with growth of aquatic plants are shown in Table 6. In most cases, it appears that optimal carbon dioxide levels for growth are close to the current and projected levels of carbon dioxide in water in equilibrium with air. Because plant growth is dependent on a variety of nutrients, including nitrogen and phosphorus, carbon limited situations are not frequent, even given present atmospheric levels of carbon dioxide. In addition, the carbonate buffer system and bacterial production also act as sources of carbon dioxide, and further reduce the likelihood of carbon-limited situations (Rich et al., 1972; Kuentzel, 1969). This effect was demonstrated by Schindler and coworkers (Schindler, 1977; Schindler and Fee, 1973; Schindler and Brunskill, 1977), who increased the nitrogen and phosphate inputs to a natural lake and found that the flux of carbon dioxide from the atmosphere was sufficient to support the additional phytoplankton growth. These workers felt that the dominance of bluegreen algae in the lake did not result from low levels of carbon, but rather from the low nitrogen:phosphorus ratios. In contrast, other investigators feel that low carbon dioxide levels limit the production of green algae, and thus permit the phytoplankton community to become dominated by bluegreen algae. This hypothesis was criticized by Goldman et al. (1974), who found no evidence that the succession of algal species was related to variations in carbon dioxide levels. James and Lee (1974) modeled inorganic carbon limitation in natural waters and estimated that carbons should not be limiting unless pH increased by 2 units.

The situation appears to be similar in the ocean, where the tremendous buffering capacity generally ensures that carbon will not be limiting. Although some reports of carbon-limited situations in the ocean exist, nitrogen is the primary limiting nutrient (Small et al., 1977). Because of this, the amount of "new" carbon dioxide in the ocean that can be assimilated by phytoplankton will be determined by the amount of "new" nitrogen that is available. However, Deuser (1979) suggests that greater nutrient inputs and increased sedimentation in near-shore waters could result in the sequestering of significant quantities of organic carbon in these areas.

Given these findings, it is unlikely that an increase in atmospheric carbon dioxide from 300 to 600 ppm will result in increased phytoplankton productivity except in areas such as fish culture or sewage treatment ponds that have a substantial excess of other limiting nutrients, including nitrogen and phosphorus (Boyd, 1973; Skicko and Reagan, 1979). These nutrient rich areas will probably respond with increased algal blooms. If the blooming species are not typically subjected to predator pressure, then nuisance blooms are likely to occur with a concomitant drop in water quality. If the

Table 6

CARBON DIOXIDE CONCENTRATIONS AS THEY AFFECT GROWTH IN AQUATIC PLANTS

Carbon Dioxide Concentration--mg/l	Effect	Reference
VASCULAR PLANTS		
0.45-75 mg/l (0.03% and 5%)	Lower level inhibited growth of *Myriophyllum spicatum*	Amundsen and Brenkert, 1978
0.52-0.79 0.91-1.32 1.35-1.57	20°C 25°C 30°C Optimal carbon dioxide levels nearly constant at given temperature range over different pH levels for *Elodea densa*	Gates, 1976
BRYOPHYTES		
0.09-0.26 (2-6 moles/l)	Compensation point for aquatic bryophytes	Bain and Procter, 1980
ALGAE		
0.009-0.44 (0.0002-10.0 mol/l)	Growth limiting levels for *Anacystis nidulans*, depending on phosphorus (59-580 g/l) and light (280-915 lux)	Young and King, 1980
0.02-0.88 (0.5-20.0 M)	Compensation point for *Chlorella vulgaris* at light intensities of 4,000-5,000 lux; at these carbon dioxide levels the growth (new biomass) balances the loss of biomass from the algal sinking rate	King and Hill, 1978
0.04-3.3 (1-75 mol/l)	Growth rate of *Asterionella formosa* responsive in this range	Talling, 1978
0.06-0.12 (40-80 ppm)	Growth limiting levels for *Chlorella vulgaris* at light intensities of 22.6-81.0 W/m^2	Markl, 1977

Table 6 (Continued)

Carbon Dioxide Concentration--mg/1	Effect	Reference
0.07 (1.5- x 10^{-3} mmol/1)	Compensation point for *Chlorella vulgaris*	Nielsen, 1966
0.44	Level of corresponding to maximum photosynthesis in *Chlorella*; this level is only 1% of the level used by marine flagellate *Coccolithus huxleyi*	Fogg, 1968
0.44 (10^{-5}M)	Limiting level in algal cultures	Ogawa and Aiba, 1978
0.45, 2.24, 4.48	No increase in growth at higher levels compared with low levels in acclimated cultures of *Skeletonema costatus* and *Isochrysis galbena*; growth was nitrogen limited	Small et al., 1977
0.45 and 29.9	Growth stimulated at higher level; also comparatively higher nitroreductase activity in *Scenedesmus obliqus*	V'nhova-radeva, 1980
0.7-14.0	Did not result in increased growth of *Thalassiosira pseudonana* cultures in bottles although addition of carbon dioxide enhanced growth in batch cultures	Pruder and Bolton, 1979
0.88 (0.02 mmol)	Limiting level of eutrophic algae	Moss, 1973
0.88-3.96 (less than 0.02-0.09 mmol/1)	Carbon dioxide range used by shell-less strain of *Thus huxleyi*	Nielsen, 1966
2.2 (0.05 mmol/1)	Limiting level for oligotrophic algae	Moss, 1973

Table 6 (Concluded)

Carbon Dioxide Concentration--mg/l	Effect	Reference
4.4 (10^{-4} M)	Not limiting level in algal cultures	Ogawa and Aiba, 1978
15.0 (1% CO_2 in air)	Near optimum level for maximum growth in Chlorella	Kraus, 1973
15 (1% CO_2 in air)	Lower levels limiting for Chlorella grown in nutrient rich media; atmospheric supply of carbon dioxide insufficient to permit maximum growth rate	Skicko and Reagan, 1979

blooming species are subjected to high predator pressure, then overall productivity will increase due to food chain inputs (Patrick, 1981).

In low alkalinity waters, higher levels of carbon dioxide could reduce the competitive edge of phytoplankton that utilize bicarbonate ion as a carbon source. On the basis of very limited data (Amondsen and Brenhert, 1978), it appears that aquatic macrophytes have a higher requirement for carbon dioxide than phytoplankton. Because these plants are generally associated in some way with the sediments, their proximity to the overlying water that has been enriched by bacterial carbon dioxide production makes it unlikely that their growth would be limited by carbon dioxide under field conditions.

Changes in Water Quality

Carbon dioxide primarily affects water quality by contributing to the carbonate buffer system. Addition of carbon dioxide generally results in an increase in bicarbonate ion and a small decrease in pH. Estimates of the magnitude of such changes in water quality vary, but they are generally thought to be small for the range of carbon dioxide concentrations considered here.

Brewer (1978b) showed that the carbon dioxide content of the ocean has already increased slightly in response to an atmospheric increase of approximately 50 ppm that occurred in the period from the mid-1800s to 1972. Roether (1980) presents a comprehensive review of the effect of the ocean on the global carbon cycle and also indicates that inorganic carbon in the ocean will increase only moderately in response to an atmospheric increase to 600 ppm. Elliott and Machta (1979) concluded that a twofold increase in atmospheric carbon dioxide would reduce the ocean pH from 8.7 to 7.8 and carbonate ion from 250 micrometers/kg to 130 micrometers/kg. Such a change would still leave the surface waters of the ocean threefold saturated with calcite and twofold saturated with aragonite. These changes should be well within the tolerance ranges of marine organisms, except possibly those organisms such as coralline algae and foramanifera (coral-like organisms) that precipitate high levels of magnesium calcite. Elliot and Machta felt, however, that a fourfold increase in atmospheric carbon dioxide levels would decrease pH to 7.2 and would cause stress for organisms that produce carbonate skeletons. Localized fauna that generally inhabit carbon dioxide poor areas (upwelling and arctic) might also be affected.

Revelle et al. (1980) felt that a fourfold increase in carbon dioxide levels would decrease ocean pH only to 7.5. Their main concerns were the effect of increased carbon dioxide on primary productivity in areas (such as estuaries) where other nutrients are not lacking, and the effects of lower pH and high carbon dioxide levels on early life stages of fish and zooplankton. Our own calculations indicate that pH changes in the ocean for the projected carbon dioxide level of 600 ppm will be on the order of 0.03 pH units. In waters with lower pH values, the change will be greater; approximately 0.1 units at pH 7 and 0.4 units at pH 6. However, the presence of other buffering systems such as phosphates or sulfites will reduce these pH changes.

The world's estuaries, which yield a high proportion of commercially important fish and shellfish, may or may not be affected more than open ocean environments. The American Association for the Advancement of Science (AAAS, 1980) states that estuarine systems are relatively poorly buffered against pH changes and suggests that they would be more sensitive to increased carbon dioxide levels. However, because of greater availability of nutrients in these areas and input of potential buffering materials from runoff, estuaries may actually be more resistant to changes in water quality associated with increased carbon dioxide levels than the open ocean.

It seems to us that the most sensitive areas would be freshwater lakes with limited watersheds and low buffering capacities, i.e., the same areas currently identified as sensitive to acid precipitation. However, even in these areas, the addition of carbon dioxide will not reduce the pH to less than 5.6 and would actually add to the existing carbonate buffer system, as explained under "Background" of this section. In addition, cold water systems may be of greater concern than warm water systems, because of the higher solubility of carbon dioxide at low temperatures. As Table 4 indicated, carbon dioxide is twice as soluble at 0-3°C than at 25°C, and is approximatey 60% more soluble at 10°C than at 25°C. Cold water areas include the polar oceans, areas of deep upwelling, and lakes and rivers occurring at high elevations and latitudes. Because of the shorter growing seasons or lack of nutrients often associated with these areas, compared to warm water systems, it is less likely that additional carbon dioxide will be taken up by algae. It will therefore be more available in the water column. Typically, the biota associated with these habitats are not very resistant to environmental changes. Consequently they could be directly impacted by carbon dioxide levels that would not affect more resilent systems.

Human Health Effects

Our conclusion, based on a literature review and on telephone interviews with physicians and pulmonary physiologists, is that a doubling of current ambient concentrations of carbon dioxide to 600 ppm will probably have negligible direct human health effects. This conclusion applies not only to normal, healthy individuals, but also to potentially sensitive populations.* The main reason that an increased level of carbon dioxide is not expected to have any significant effect is that endogenous human production of carbon dioxide generates an alveolar (deep lung) concentration of approximately 40 torr,** or about 5% of the concentration of the atmosphere at sea level. This is nearly two orders of magnitude greater than 600 ppm (about 0.06%). Individuals with chronic disease, particularly pulmonary disease, may generate even higher endogenous concentrations of carbon dioxide, in comparison with which 600 ppm appears even more marginal.

Humans are commonly exposed to concentrations of carbon dioxide in the range of 600 ppm, both in occupational and residential settings. As energy conservation trends result in increasingly air-tight buildings, integrated indoor exposures to carbon dioxide may reach 1200 ppm or more (Spengler, 1981). Even at this concentration adverse health effects are not expected. This conclusion is not, however, based on any published investigations, because our literature search turned up no studies of effects at such low levels.

In the following sections, we will briefly discuss basic aspects of carbon dioxide metabolism. These discussions are followed by a review of a few adverse effects reported to be associated with low levels of ambient carbon dioxide.

Normal Physiology of Carbon Dioxide

Carbon dioxide is the final oxidation product of normal energy-generating processes in the human organism; it is transferred from all metabolically active tissues through the blood to the pulmonary capillaries, where it diffuses and is transported into alveoli to be exhaled during ventilation. Although numerous factors affect the concentration of carbon dioxide in blood, the principal physiological roles played by this gas are regulation of respiration and blood pH. The following paragraphs will consider these roles in greater detail.

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[*] Such populations might include premature infants, persons with cardiopulmonary disease (e.g., angina pectoris, asthma, emphysema, and chronic bronchitis), persons taking drugs such as acetazolamide (a carbonic anhydrase inhibitor used to treat glaucoma), and persons with various kinds of anemia.

[**] A torr is a unit of pressure equal to 1/760 of an atmosphere. An atmosphere is a unit of pressure equal to the pressure of the air at sea level or approximately 14.7 pounds to the square inch (psi).

Carbon dioxide is present in blood in three forms: (1) as dissolved gas; (2) as bicarbonate ions (HCO_3); and (3) bound to the terminal amino groups of various proteins, primarily hemoglobin. About one-third of carbon dioxide is found in red blood cells, the remaining two-thirds is in plasma. The total carbon dioxide in arterial blood is divided among these forms as follows: 90% as bicarbonate, 5% as dissolved gas, and 5% bound to protein (Wagner, 1977).

Under normal circumstances, the partial pressure of carbon dioxide in arterial blood is the most important stimulus to ventilation (West, 1979). The normal range for arterial partial pressure of carbon dioxide is 37 to 43 torr, which does not vary with age (West, 1977). Under normal circumstances the homeostatic control of this parameter is remarkably precise, probably remaining within 3 torr while individuals are awake, including periods of exercise as well as less strenuous activities. The arterial partial pressure of carbon dioxide may increase slightly more during sleep.

An increase in arterial partial pressure of carbon dioxide results in increased ventilation and expiration of carbon dioxide, returning the arterial partial pressure of carbon dioxide to normal. This ventilatory response is mediated principally through central chemoreceptors located near the ventral surface of the medulla. These sensors react to changes in the pH of the cerebrospinal fluid due to diffusion of carbon dioxide across the blood-brain barrier. In studies investigating this ventilatory response in normal young men, the carbon dioxide sensitivity averaged 2 to 5 liters increase per minute per torr increase of partial pressure of carbon dioxide (Berger et al., 1977). For example, ventilation in submarine crews increased by 40-63% during patrol and artificial experimentation conditions (Schaefer, 1979). The ventilatory drive in response to increased arterial carbon dioxide has been reported to be diminished in older individuals, trained athletes, and premature and full-term newborn infants (Berger et al., 1977; Elegbeleye and Femi-Pearse, 1980; Bryan et al., 1976; Frantz et al., 1976).

Ventilation plays an important role in determining the acid-base status of the blood and tissues. Precise regulation of intra- and extracellular pH is required for maintenance of normal enzyme activity, hemoglobin oxygen saturation, tissue oxygen use, and so forth. The pH of the blood is maintained through a carbonic acid and bicarbonate buffer system, assisted by the lungs' and kidneys' excretion of excess acidity when necessary. Exhalation of carbon dioxide is the predominant mode of elimination of carbonic acid.

The relationship of pH, bicarbonate ion and dissolved carbon dioxide is described by the Henderson-Hasselbalch equation:

$$pH = pK_a + \log \frac{HCO_3^-}{0.03\ P_{CO_2}}$$

where pK_a is the negative logarithm of the carbonic acid dissociation constant, and P_{CO_2} is the partial pressure of carbon dioxide. The value of pK_a is 6.1, and under normal circumstances the arterial bicarbonate concentration is 24 millimoles/liter (mmol/l) and partial pressure of carbon dioxide is 40 torr. Substituting these values in the Henderson- Hasselbalch equation gives a normal arterial pH of 7.4.

In this equation the bicarbonate concentration is affected principally by the kidney, whereas the partial pressure of carbon dioxide is a function of the lungs' activity (West 1979). Disturbances in the bicarbonate/carbon dioxide ratio due to problems with the kidneys or lungs (or other systems that affect renal or pulmonary functions*) will alter the pH. Changes in the blood pH elicit compensatory responses by the lungs and kidneys (unless these organ systems are diseased and incapable of responding). For example, someone with chronic obstruction pulmonary disease (e.g., asthma, emphysema, chronic bronchitis) will retain excess carbon dioxide in the blood, depressing the pH in a condition called respiratory acidosis. Prolonged exposure to approximately 1% carbon dioxide causes a mild resipiratory acidosis (Schaefer, 1979). In persistent respiratory acidosis, the kidneys will attempt to compensate by excreting less bicarbonate than usual, in order to increase the bicarbonate/carbon dioxide ratio.

Under ordinary circumstances the concentration of carbon dioxide in the deep lungs (alveoli) is close to its partial pressure in arterial blood--about 40 torr. In persons with respiratory acidosis, compensated or not, the concentration of carbon dioxide is even higher. In either case the pulmonary concentration of carbon dioxide is at least 5% of the combined concentration of gases at sea level (40/760). This is almost two orders of magnitude greater than the ambient level of 600 ppm that is the proposed upper limit for this study. Even if the concentration of carbon dioxide in energy-saving buildings were to increase to 1,200 ppm, more than a thirtyfold difference between ambient concentrations and endogenously generated carbon dioxide would remain. Such large numerical safety factors have led SRI (and the sources we interviewed) to conclude that human health effects due to increased ambient levels of carbon dioxide are improbable, even among potentially sensitive populations. Furthermore, persons whose pulmonary function is compromised to the extent that they might be affected by such a physiologically marginal increment of carbon dioxide would probably be under medical supervision in a hospital or chronic care facility, that has an auxiliary supply of oxygen to add an extra margin of safety.

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* Scores of nonrenal, nonpulmonary pathophysiologic processes can alter the pH. Examples include poorly controlled diabetes, which can result in very high concentrations of metabolically generated acids, and drugs that depress the respiratory center in the brain, resulting indirectly in a build-up of carbon dioxide in the blood.

Adverse Effects at Enhanced Levels

At high ambient concentrations (17-30%), carbon dioxide can act as an asphyxiant, but physiologic effects in humans and animals have been reported at lower levels (0.5-5%) as well. Symptoms and signs associated with acute exposure to high concentrations of carbon dioxide (at least 5% or 50,000 ppm) include unconsciousness, convulsions, eye flickering, perspiration, flushing, dilated pupils, leg flexion, torsion spasms, dizziness, restlessness, headache, shortness of breath, vomiting, hallucinations, increased blood pressure and pulse rate, and increased respiration (NIOSH, 1976). Almost all chronic exposure of humans has involved concentrations between 2 and 5% carbon dioxide, although some clinical investigations on submarine crews have involved prolonged exposures to about 1% carbon dioxide. Reported effects of chronic exposure of humans to concentrations of carbon dioxide above 2% (20,000 ppm) include changes in blood pH and bicarbonate, increased respiratory rate and depth, headache, somnolence, mental confusion, irritability, engorged retinal veins, airway constriction, and unconsciousness (NIOSH, 1976). SRI's search of recent literature did not reveal any published reports involving exposure of humans or animals to ambient levels as low as that under consideration in this document. Thus, our conclusion that any adverse effects on human health are unlikely (a conclusion supported by everyone we interviewed) is based on inference only. The following paragraphs list the principal potential adverse effects noted in recent experimental investigations with increased ambient levels of carbon dioxide.

Sudden Infant Death Syndrome (SIDS)

Among other hypotheses, it has been conjectured that build-up of carbon dioxide in the air above infant cots may be responsible for sudden infant deaths (Seifert, 1979). Infants who have had aborted SIDS epsiodes and parents of such children have been reported to have abnormal ventilatory responses to carbon dioxide (Haddad et al., 1979; Berman et al., 1981). Even if increased levels of carbon dioxide are implicated in the etiology of SIDS, the addition of 0.06% (600 ppm) to the ambient air would be only a marginal increment and would probably have a negligible effect.

Effects on Calcium Metabolism

Studies on guinea pigs exposed to 0.5% carbon dioxide (5,000 ppm) for periods up to 8 weeks demonstrated significant increases in plasma calcium and in renal calcification relative to control animals; these effects were similar to earlier findings of renal calcification at 1% carbon dioxide (Schaefer et al., 1979a, b). These changes were reversible after an 8-week recovery period.

These findings may have some relevance for humans exposed to increased levels of carbon dioxide. "Plaques of hypercalcification" in the fingernails have been reported in submarine crew members exposed to 1.5% carbon dioxide (Schaefer et al., 1963). This abnormality was attributed to a mild respiratory acidosis, during which some of the increased carbon dioxide was thought to be stored in bone, releasing calcium and phosphorus into the blood. Several studies on submariners' blood chemistry have shown a marked, sustained decrease (40-70%) in urinary calcium excretion, which starts within days of exposure to an environment of 0.7-1.5% carbon dioxide (Davies and Morris, 1979). This reported reduction in Ca^{+2} excretion may continue for weeks to months following cessation of exposure to such elevated carbon dioxide levels. Several investigators have conjectured that chronic human exposure to carbon dioxide results in kidney-mediated calcium retention, which in turn may cause calcium nephropathy (Davies and Morris, 1979). However, in the submarine studies, it has been proposed that, although the short-term effects on calcium metabolism may result from exposure to increased concentrations of carbon dioxide, the longer term effects may result principally from lack of vitamin D caused by isolation from sunlight (Davies and Morris, 1979). More recent research of active and retired submarine crews indicates that carbon dioxide effects on calcium metabolism are quite subtle with respect to overall bone metabolism, and that any effects of prolonged exposure to 0.75-0.8% carbon dioxide are reversible (Messier, 1981).

Changes in Pulmonary Ultrastructure

As noted previously, endogenous carbon dioxide concentrations in the deep lung may reach approximately 5% of the total atmospheric gas. However, exposure of guinea pigs to 1% carbon dioxide for at least four weeks has been reported to cause structural changes in precursors to cells lining the lungs (pneumocyte II cells). The investigators (Douglas, 1979) postulated that the increases in size and number of pneumocyte II cells was due to a mild, uncompensated respiratory acidosis observed in the experimental animals. These effects were slowly reversible during a postexposure recovery period.

These experimental results have recently been replicated at a concentration of 0.5% carbon dioxide (Messier, 1981). This concentration is slightly more than four times the potential indoor concentration of carbon dioxide (1,200 ppm) that could be encountered with an increase of the ambient level to 600 ppm. Although our interviewees did not consider the potential proliferation of pneumocyte II cells to be a major problem, assuming current atmospheric carbon dioxide levels are doubled, they did feel that more research should be undertaken to elucidate the significance of this finding (see Section IV).

III POLICY IMPLICATIONS

This section presents four possible forecasts of future atmospheric carbon dioxide levels and defines the carbon dioxide issue in terms of environmental and human health implications. Potential carbon dioxide control strategies are also discussed.

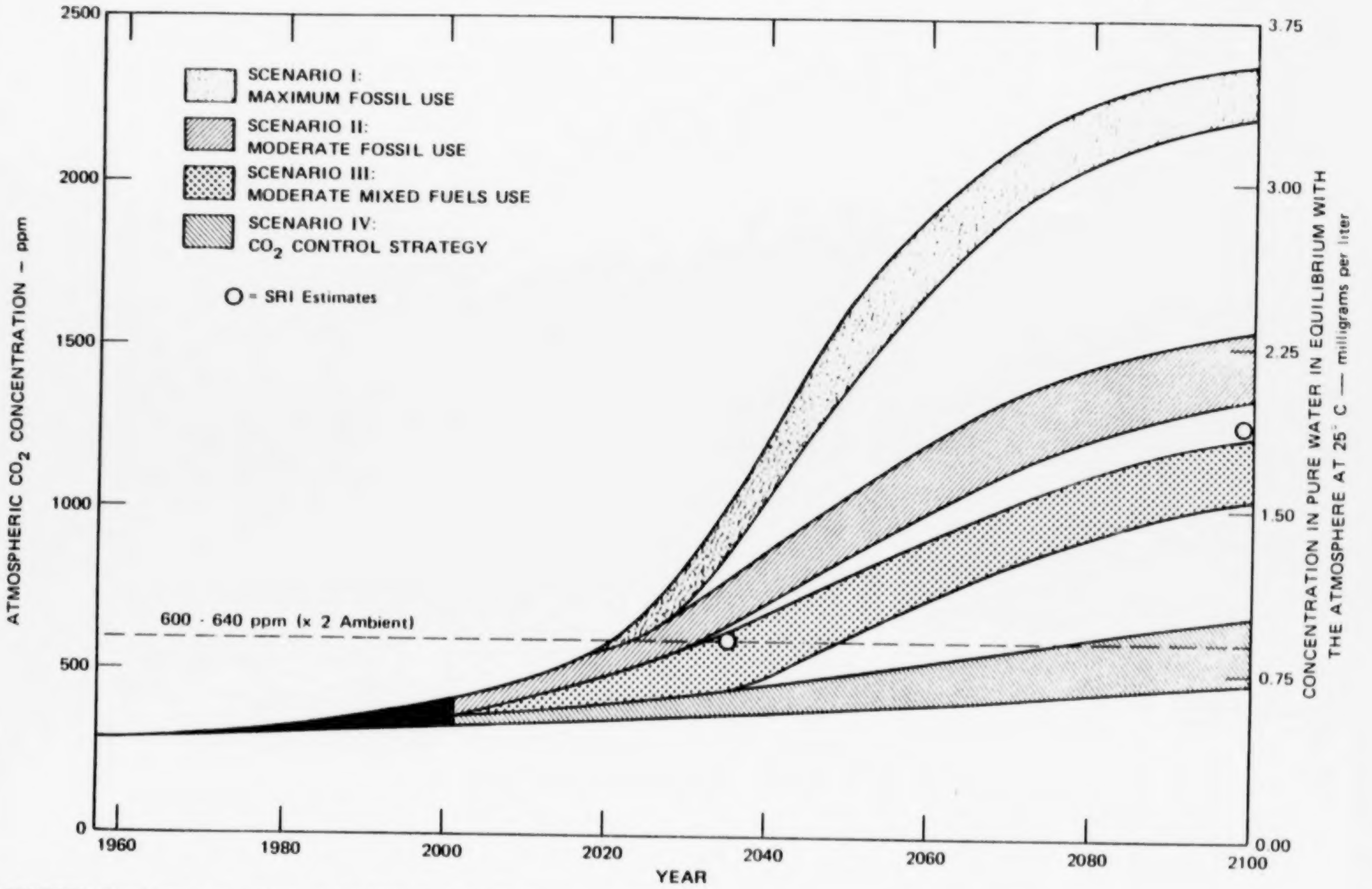
Projected Atmospheric Carbon Dioxide Level Scenarios

Several published studies present trend information on future atmospheric carbon dioxide levels (e.g., Hoffert, 1974; Smil and Milton, 1974; Keeling and Bacastow, 1977 as cited in Bach, 1978; Zimen et al., 1977; Bach, 1978; Wong, 1978; Emanuel, 1980; and Niehaus, 1976 and 1980). The various projections can be summarized in four basic scenarios as shown in Figure 1. The greatest actual levels and the most rapid rates of carbon dioxide increase are represented by Scenario I, in which all readily available fossil fuels are burnt as quickly as possible. We believe that this is an unlikely scenario. It is largely based on Keeling and Bacastow's early exhaustion estimates. These were made in 1977, before the second petroleum crisis that resulted in an almost 90% increase in oil prices between 1979 and the end of 1981. This scenario does, however, establish the probable upper limit for possible increases in carbon dioxide levels.

At the other extreme, and probably equally as unlikely, is the carbon dioxide control strategy. This scenario would require an almost complete conversion to nuclear or other nonfossil energy by the second half of the next century, or a dramatic decrease in growth energy demand to a constant rate of 1%, or the implementation of a massive carbon dioxide control program, as described in this Section.

In between are two more likely scenarios. Scenario II is based on a moderate rate of use of fossil fuels and a gradual transition to alternative energy sources by 2100. The annual average energy growth rate for this scenario is 3.5 to 4.5%. Scenario III assumes earlier and greater use of alternative fuels, with nuclear and solar sources filling 25% of the world's energy demand by 2000, or a decrease in growth in world energy demand to a 2.5 to 3.0% average annual rate.

By extrapolating SRI's latest projected world energy consumption forecast figures for fossil fuels for the years 2000 to 2100, and by assuming that one-half of the fossil fuel input will remain in the air as it evidently has from 1958 to the present, we project that atmospheric carbon dioxide levels will double by about 2035. By 2100, we project that carbon dioxide concentrations will reach about 1,300 ppm. These figures are intended to be only rough estimates, not based on sophisticated procedures. Interestingly enough, however, they fall between the levels projected for Scenarios II and III.



SOURCES: Based largely on Niehaus, 1976, 1980; Bach, 1978; Zimen et al., 1977; and SRI International projections, 1981.

FIGURE 1. FOUR PROJECTED SCENARIOS OF CARBON DIOXIDE LEVELS IN THE ATMOSPHERE

Environmental and Human Health Implications

The information presented in Section II and the projections just given indicate that there is little likelihood of adverse impacts due to direct effects of increased atmospheric carbon dioxide levels on most of the terrestrial biota until the year 2050. At this time, certain sensitive species, especially C4 plants, might begin to show reduced growth rates. However, most plant species might actually benefit from the increases in carbon dioxide up to the year 2100. An actual evaluation of the desirability or undesirability of the expected terrestrial ecological effects depends to a large degree on our management objectives. Do we want to increase the marketable yield in the most cost-effective way (change nature to serve man), or do we want to perpetuate a relatively undisturbed, self-supporting system of diverse biota (influence man to conform with nature)? In the United States, we have moved in both directions. On the one hand, we are seeing work on the frontiers of biotechnology open a new world of promises and concerns. On the other hand, we are becoming increasingly aware of the energy efficiencies inherent in natural ecosystems. It is becoming apparent that we need not only to learn how biota have adapted and can adapt to higher carbon dioxide concentrations, but also to develop better ways to manage our biological resources to take advantage of the effects of these increased carbon dioxide levels on our terrestrial ecosystems.

The data we reviewed in Section II suggest that potentially deleterious effects may be seen earlier in the aquatic ecosystem than they will be in the terrestrial ecosystem. If Scenario I is followed, adverse effects on aquatic life may be evident as early as 2040. By this time the reproductive success of species in certain important commercial fisheries might be reduced, particularly that of cold water fishes. In addition, algal blooms in nutrient-rich areas might be more frequent. Aquatic organisms must interact with the carbonate-bicarbonate buffering system of the water and the resulting pH changes. The projected carbon dioxide levels for all the scenarios except Scenario IV would indicate that several aquatic organisms, including species that produce carbonate skeletons might be under stress by 2100. The aquatic ecosystems thus present quite a different picture from that presented by the terrestrial ecosystems, and the former are apparently much more sensitive to changes in atmospheric carbon dioxide levels. Additional research to estimate more reliably the magnitude and extent of the potential adverse effects on aquatic organisms is necessary.

There appears to be a substantial margin of safety for human health effects. The Office of Safety and Health Administration (OSHA) time-weighted carbon dioxide standard for an 8-hour day is 5,000 ppm. However, most occupational exposures are intermittent, except for those experienced by submarine crews who commonly are subjected to concentrations of 10,000 ppm. In 1976, the National Institute of

Occupational Safety and Health (NIOSH) recommended that the permissible level for carbon dioxide be increased from 5,000 to 10,000 ppm for 10 hours per shift in a 40-hour work week. They also proposed a ceiling concentration of 30,000 ppm for 10 minutes (Higgins, 1977).

Assuming that indoor concentrations are double that of ambient outdoor concentrations, only under the unlikely path of Scenario I would the 5,000 ppm standard be approached, and then not until 2100. However, chronic exposure of 5,000 ppm might possibly adversely affect the calcium metabolism of humans.

It is becoming increasingly clear, however, that although a larger atmospheric concentration of carbon dioxide is a gradually developing phenomenon, the decisions we make today will limit our options for dealing with the potential problems in the near and distant future. This is true both because of the long residency in the air of carbon dioxide from anthropogenic sources and because of the time a society requires to adapt successfully to altered environmental conditions. The carbon dioxide issue is a complex one with global implications. As indicated by the AAAS panel investigating potential economic and geopolitical consequences, the potential effects of increased carbon dioxide must be viewed in the perspective of other large-scale social, political, and natural events that are likely to occur in the next 50 to 100 years.

We have only briefly analyzed one aspect of this multifaceted issue--the potential direct biological effects. Our results indicate that we should be developing both an adaptive strategy that takes advantage of the potential positive effects of enhanced carbon dioxide levels on terrestrial ecosystems and a preventive strategy to help ameliorate potential deleterious effects on the aquatic system. Human health effects appear to be of little concern at the levels projected to the year 2100.

Control Strategies

In this subsection, we address the possible strategies for controlling the increase in atmospheric concentrations of carbon dioxide. Assessing the benefits of adopting any strategy will depend on determining the possible negative effects of taking no action. Our discussion of control strategies is predicated on the assumption that increases in atmospheric carbon dioxide will have some significant negative consequences.

SRI Workshop

A workshop was held on November 11, 1981, at SRI International to "identify" and "speculate" about carbon dioxide control technologies and strategies.* The fourteen invited participants represented a wide range of environmental, engineering, and economic disciplines (see Appendix B). Before the meeting, abstracts of articles relating to atmospheric carbon dioxide control and the carbon cycle were distributed (see Appendix B).

Although present scientific opinion about the effect of atmospheric increases in carbon dioxide varies widely, for the purposes of the workshop, certain assumptions were made:

- In the next 50 years, atmospheric carbon dioxide concentrations will double from their present levels. The sources of these increases will largely be anthropogenic.
- Doubling the present carbon dioxide levels will produce adverse environmental effects, largely climatic.

General Conclusions. The carbon dioxide control problem was generally viewed as one involving the identification and implementation of economically sound methods to decrease the rate of anthropogenic introduction of carbon dioxide into the atmosphere to levels that nature can assimilate, either through carbon fixation or through other carbon sinks. Thus the problem could be described, in electrical utility terminology, as a "peaking problem."

No single method emerged as the single best control option, perhaps at least partly because of the massive amounts of carbon dioxide that would have to be controlled. However, several practical and many impractical strategies were identified as partial solutions. The best overall strategy might be to implement a program consisting of a package of various methods, depending on the specific problems and resources available at a given site. Alternatively, society could learn to adapt to the environmental consequences of higher carbon dioxide levels.

Some of the control options identified would take 50 years or so to be fully implemented, and thus would have to be initiated now to be effective. Other methods, such as installing emission source controls, could be fully implemented immediately. However, because of the substantial residence time of a large fraction of the atmospheric carbon dioxide (up to 1,000 years), even the strategies that would have immediate effect would not be able to reduce the levels of carbon dioxide for several centuries. These methods would only be able to

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[*] "Identify" and "speculate" are terms used by EPA in their Request for Proposal for this study (RFP No. DU-81-B169). The workshop was more of a brainstorming session than an exchange of scholarly research.

prevent further increases. If the goal is to maintain present levels of atmospheric carbon dioxide, control measures would have to be initiated today.

Many of the potential strategies identified could be taken into consideration in the siting of new power plants and other point sources, as well as in the development of the energy policies for the country. To address the problem adequately, however, international cooperation will be required. The developing countries are soon expected to be producing more carbon dioxide than the United States does.

Because of the potential seriousness of the carbon dioxide problem, the general consensus was that basic scientific research should be accelerated in such areas as understanding the dynamics of the carbon cycle and the development of global climatic models using real-world data to estimate the effects of atmospheric carbon dioxide. A specific need is to quantify the carbon fluxes among the world's exchangeable carbon reservoirs. A considerable range of opinion exists today concerning the sizes of the carbon pools and the flux rates involved in the carbon exchanges. Particularly unclear are the roles that the biosphere and soils play in the carbon cycle, even though there have been recent conferences on these subjects.* Only recently have scientists at SRI discovered that ordinary sand, acting as a photocatalyst, is indirectly responsible for releasing considerable amounts of carbon dioxide into the earth's atmosphere. Sancier and Wise (1981) estimate that the solar-assisted photoproduction of carbon dioxide on a global scale is nearly 10% of the net rate of carbon dioxide production from the combustion of fossil fuels. In addition, we still have only rough estimates of how much biomass exists today in the world and of the rates and types of land use changes occurring on a global basis. The dynamic nature of these changes must also be taken into consideration developing a realistic view of the global carbon cycle. No further engineering research on carbon dioxide control strategies was recommended until some of these basic scientific questions about the carbon cycle have been more precisely answered.

One final observation concerns the inevitability of implementing some of the so-called carbon dioxide control strategies, particularly those relating to altering energy use patterns. Several of these

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* These include the workshops the U.S. Department of Energy has sponsored in connection with their Carbon Dioxide Effects Research and Assessment Program. See Armentano, 1980; Armentano and Hett, 1980; Brown et al., 1980; and Miller, 1981.

"strategies" will probably come about regardless of the carbon dioxide issue in response to economic factors that will force us to use our energy resources more efficiently.

Specific Control Methodologies. Six categories of carbon dioxide control options were discussed. They are summarized in Table 7 and briefly described below.

I. Increasing the Rate of Carbon Fixation or Mass Transfer

Three basic pathways were discussed under this general category: increasing the carbon fixation rate into living matter; increasing the rate directly into inorganic material; and increasing the rate into an intermediate inorganic sink. Three specific examples under the first pathway were considered: utilizing bioengineering techniques; increasing terrestrial seeding; and conducting aquatic seeding programs.

Genetic engineering might be able to change the photochemistry of microorganisms or plants to increase the quantum efficiency of their use of sunlight and thus their rate of carbon fixation. This method could be implemented as either a point-source or nonpoint-source technique. Point source methods would require large containment structures and large surface areas. Protein ponds (biological "scrubbers") containing a "super bug" that has a much higher rate of photosynthesis than known organisms might be developed. If available sunlight were a problem, one might be able to use chemosynthetic organisms that depend on inorganic chemicals alone for their energy source to fix the carbon. One might also be able to develop an in vitro coral polyp. These point source methods would probably be expensive to implement. Compared to chemical scrubbing systems, they would have a slow rate of absorption and a low carbon dioxide carrying capacity.

One might also be able to apply genetic engineering techniques at the general atmosphere level, e.g., develop forests that are more efficient in carbon fixation. Plant breeders have in fact been doing this for several decades. Bioengineering might be to locate specific genes at the biochemical level that would allow C3 plants to incorporate a C4 carbon fixation pathway, and thereby reduce photorespiration and increase net photosynthetic incorporation.*

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* Photorespiration is the condition during illumination in which plants respire away early products of photosynthesis. C3 and C4 plants refer to two different metabolic pathways in which vegetation assimilates carbon dioxide. C4 plants have very low or essentially no photorespiration, whereas C3 plants respire away perhaps as much as 50% of their early photosynthetic products. However, C4 plants appear to be less well adapted to use high carbon dioxide levels than are C3 plants. See Section II for more details.

Table 7

CARBON DIOXIDE CONTROL STRATEGIES

- I. Increase the Rate of Carbon Fixation or Mass Transfer
  - A. Increase the rate of carbon fixation in living matter
    - 1. Utilize bioengineering techniques
    - 2. Increase terrestrial seeding
    - 3. Conduct aquatic "seeding"
  - B. Increase the rate of carbon fixation directly into inorganic material
    - 1. Form calcite (calcium carbonate)
    - 2. Develop a dissolution substance
  - C. Increase the rate of carbon fixation into an intermediate inorganic sink
    - 1. Transfer the carbon dioxide to the deep ocean
    - 2. Transfer the carbon dioxide to terrestrial sinks
- II. Change Fuel Use Strategy
  - A. Cease fossil fuel use, switch to big nuclear facilities
  - B. Cease fossil fuel use, switch to soft energy pathways
  - C. Use fossil fuels more efficiently
    - 1. Tune up power plants
    - 2. Remove carbon dioxide prior to fuel use
- III. Change Energy Use Patterns
  - A. Alter mobile source use
  - B. Alter agricultural practices
  - C. Conserve energy in general
  - D. Control population growth
- IV. Use Emission Source Controls
  - A. Use chemical processes
  - B. Use institutional methods
- V. Use Institutional Controls to Adapt Society to Altered Atmospheric Carbon Dioxide Levels
- VI. Implement Exotic Strategies
  - A. Use extraterrestrial sinks
  - B. Develop closed agriculture-energy production systems

However, the mechanisms and genes involved in these photosynthetic processes have only begun to be elucidated, even though the biochemistry of carbon fixation is fairly well understood in C3 and C4 plants. The ability to develop super photosynthetic organisms appears to be several decades away even though biotechnology is rapidly advancing. Participants also expressed concern about the possibility that super organisms could get out of control once they are released into the natural environment, which would perhaps lead to a situation similar to the water hyacinth problem.*

The specific example discussed under the terrestrial seeding category was an accelerated reforestation program. Such a program would act as a temporary sink as long as the forests were left intact. This strategy would have many other environmental benefits, including soil protection. Some of the major limitations of such a scheme include the available supply and high costs of fertilizer required for an accelerated project; the amount of available land for reforestation; and the sociopolitical barriers that would be involved in implementing a worldwide reforestation program. However, most other international efforts would probably face similar sociopolitical barriers.

Under the topic of aquatic seeding we discussed the possibility of fertilizing the ocean with the limiting nutrient (commonly phosphorous) and growing huge amounts of plankton, which would rapidly die and be deposited in the ocean depths. Because phosphorous fertilizer itself may be a limiting factor, use of organisms with low phosphorous requirements or bioengineering development of such an organism was suggested. Participants noted that such a scheme could easily lead to an ecological disaster. Rapid biomass accumulations might occur at the expense of other organisms of higher value to man, or these organisms might produce toxic by-products--similar to the eutrophication cases we have already witnessed, in which blue-green algae and other undesirable species have taken over. A real conflict of interest might arise if the more productive waters were fertilized, such as the shallow estuarine waters where most of our shellfish are produced.

Two examples involving increasing the rate of carbon fixation directly into inorganic materials were discussed: forming calcite (calcium carbonate) and developing a dissolution substance. No practical absorbent available in large enough quantities to form calcite was identified, although certain areas with abundant lime might be able to use this method. The idea of developing a dissolution substance that can be spread on sand or some other common substratum (with the end result of making carbon dioxide disappear) is only speculative at this point.

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* For a discussion of the potential applications of biotechnology in the energy field, see Zaugg and Swarz (1981); for a similar discussion of agricultural genetic engineering, see Kidd et al. (1981).

We also considered increasing the rate of carbon fixation into an intermediate inorganic sink such as the deep ocean or terrestrial sinks. The ocean solution was not considered practical for power plants away from the coasts because of the costs involved in transporting, pumping, and compressing the carbon dioxide. The ecological implications for coastal plants that might be able to use thermohyaline curents in their sinking model to carry the carbon dioxide away (see Marchetti, 1977, 1980) are serious; they include, for example, resulting changes due to pH shifts. Concern was also expressed about the problems of dissolving huge quantities of carbon dioxide in shallow water.

The terrestrial sink we discussed entailed the use of depleted oil wells. This method was considered a potentially practical solution only in limited cases for limited amounts of carbon dioxide, because very few sites are available. It was noted that carbon dioxide is currently being used to extract oil from depleted wells, not as a carbon dioxide control strategy, but as an oil recovery tool (see U.S. Bureau of Land Management, 1979, draft environmental statement on a pipeline to transport carbon dioxide from southeast Colorado through New Mexico to the Wasson Oil Field near Denver City, Texas).

II. Change Fuel Use Strategies*

Strategies involving ending use of fossil fuels and using fossil fuels more efficiently were discussed. One possible method would be to rely on big nuclear facilities for an all-electric economy. This strategy could result in as many economic, environmental, safety, resource, and sociopolitical problems than burning fossil fuels, if not more. These problems have been identified many times; they include nuclear proliferation and the lack of adequate supplies of uranium if we do not have breeder reactors or enrichment capabilities. In addition, implementing such a change might require acentrally directed and highly controlled operation. Furthermore, many of the developed countries' economies are now based on fossil fuels.

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* The impact of different energy options on atmospheric carbon dioxide levels has been recently reviewed by Niehaus (1980).

Alternatively, we could switch to soft energy pathways, renewable energy sources such as solar, wind, and biomass. In using soft energy pathways, one is trying to substitute low-intensity energy sources for high-initensity energy sources. Even conservative energy demand projections would indicate that we cannot develop enough soft energy facilities over the next 50 years to meet all our energy needs. Nonetheless, the use of soft energy methods is a practical partial solution and could result in a decrease in the use of fossil fuels.

Two ways of using our fossil fuels more efficiently were discussed. The first involved tuning up our power plants and thereby increasing their overall efficiency from 35 to 40%. This solution, like several others, is probably a good idea regardless of the carbon dioxide problem. If less fossil fuel must be burned for the same energy output, the rate at which carbon dioxide is introduced into the atmosphere would decrease, although the total concentration levels would continue to increase, all other factors remaining equal.

The second solution involved removing carbon dioxide before fuel use. For example, one could gasify coal and produce carbon dioxide and hydrogen, then remove the carbon dioxide and use the hydrogen in fuel cells. One still has the problem of disposing of the carbon dioxide. We could also switch to methanol as the main source of energy and thereby reduce carbon dioxide emissions by 50%. Only half of the energy produced by methanol originates from the oxidatioan of carbon; the other comes from the oxidation of hydrogen. Other processes involving the polymerization of carbon oxides were also mentioned. Although these strategies are technologically feasible, they all require vast amounts of energy to be implemented. If alternative fuels (e.g., methanol) are generated from coal (by gasification, etc.), more carbon dioxide may be generated in the overall process than is generated in direct combustion of coal. The ultimate end-use efficiency of the alternative fuel must be very high to compensate for the inefficiency of generating the alternative fuel.

III. Change Energy Use Patterns

All of the methods discussed under this category involve a radical restructuring of our life styles. Many of these changes are slowly coming about because of economic and resource considerations regardless of the carbon dioxide issue.

Four different approaches were discussed. The first involved altering mobile source uses. It was noted that transportation sources may account for roughly one fourth of the carbon dioxide emitted by man into the atmosphere. A particularly promising approach is the substitution of communication devices for transportation needs (e.g., paying one's utility bills over the telephone). Other examples discussed were changing over to mass transit or to all electric vehicles. The latter strategy would only help if the electricity is made by means other than those that require fossil fuels.

The second strategy suggested was altering agricultural practices, e.g., by reducing uncontrolled burning of forests and croplands or using biomass that would otherwise decay as fuel. One could also reduce the amount of time forest and cropland soils are bare. The removal of vegetation accelerates the release of carbon dioxide from soils.

A third strategy was to conserve energy. Industrialized countries, particularly the United States, have a great potential to conserve substantial amounts of energy without decreasing our standard of living. However, this solution would appear impractical for less developed countries.

The fourth strategy identified was controlling population growth. The fewer people we have, the less energy we require, and thus the less we need to burn fossil fuels.

It was reemphasized that basic life style changes are not driven by energy market considerations; rather, economic, resource, and other factors tend to dictate our life styles. The specific role of the goverment in this very broad area of life style change was seen as one of being sure that regulations do not favor fossil fuel use or unfairly penalize the use of nuclear energy or other non-fossil technologies.

IV. Use Emission Source Controls

Both engineering and institutional methods of controlling emissions were considered. Although several chemical processes have been developed and are known to be effective, the preferred engineering method for carbon dioxide removal from flue gas appears to be the use of MEA (monoethanolmine). The technology for these chemical removal processes is well established. However, this process would severely reduce overall power-plant efficiency, would be quite expensive considering the vast amounts of carbon dioxide that must be removed, and would only capture the carbon dioxide. One would still have to dispose of the captured gas.

Alternatively, one could apply an institutional control by levying a tax on carbon dioxide emissions. A given air quality region could have a certain maximum carbon dioxide concentration level that could not be exceeded unless one paid a financial penalty. This concept is similar to ones that are currently being applied in the United States with respect to other air pollutants, e.g., the prevention of significant air quality deterioration (PSD) requirements.

V. Use Institutional Controls to Adapt Society to Altered Atmospheric Carbon Dioxide Levels

Rather than implementing carbon dioxide control strategies, one could take a very different approach and use institutional means to adapt societies to the environmental consequences of higher carbon dioxide levels. The environmental consequences appear to be largely climatic; thus, society would have to be trained to live under different moisture and temperature conditions. For example, different agricultural practices would have to be implemented. Major problems would exist if coastal lands become submerged. Massive relocation projects would be required. This solution would appear to be practical only if the climatic shifts are gradual.

VI. Exotic Strategies

Two exotic strategies were considered. The first involved finding extraterrestrial sinks for carbon dioxide, e.g., the moon. This solution appears highly impractical at present, particularly in light of the carbon dioxide transport problems. A second strategy concerned developing a closed agricultural-energy system. Such a scheme would entail growing crops under a transparent cover, harvesting and processing the crops to remove some protein as a valuable product, using the residue as fuel for power plants, and returning the combustion carbon dioxide to the covered agricultural fields where plants would be grown in a carbon dioxide-enriched atmosphere (see Bassham, 1977). Serious economic and engineering problems are associated with this scheme, although the idea itself appears to have merit.

IV TECHNICAL INFORMATION NEEDS

Current Research on Direct Effects

Many current investigations are related to the effects of atmospheric carbon dioxide levels on plants. A few of these studies, representative of those being carried out at universities in the United States, are listed in Appendix C. The research areas covered range from basic research in the biochemistry of photosynthesis to work on optimizing the water use of agronomic crops to determining the effect of exhaust air from an animal shelter on greenhouse production. Some of these investigations are coordinated with work at U.S. Department of Agriculture field laboratories, including the DOE-sponsored program investigating the direct effects of enhanced carbon dioxide levels on field crops at the University of North Carolina, the University of Florida, and Mississippi State University.

International efforts in this area are substantial. Evidence of this activity is found in the articles published in Photosynthesis Research, an international journal published in The Hague, the Netherlands, and Photosynthetica, a similar international journal for photosynthesis research published for the Institute of Experimental Botany of the Czechoslovak Academy of Science. Both these publications cover all aspects of photosynthesis, including carbon dioxide fixation and carbon assimilation.

Several research projects that relate to the direct effects of enhanced carbon dioxide levels on aquatic ecosystems are also under way. However, we were unable to discover any published literature involving exposure of humans or animals to the concentrations of carbon dioxide considered in this study (600 ppm). Names and addresses of a few of the principal scientists actively engaged in research on direct biological effects of enhanced carbon dioxide levels are presented in Appendix D. Included are names of those studying human health effects of low (but greater than 600 ppm) carbon dioxide levels). For a more complete listing of terrestrial and aquatic ecologists, refer to AAAS (1980), pp. 71-76.

Research to date clearly indicates that ecological effects will occur if carbon dioxide concentrations were to rise to twice current levels. However, evidence on the direct changes that could occur is limited to studies on a relatively few species under a small range of conditions. We need a better understanding of both terrestrial and aquatic ecosystems before we can predict with confidence the consequences of increased atmospheric concentrations of carbon dioxide.

Potential Areas for Future Research

Several recent articles have addressed priorities in future carbon dioxide research (e.g., Lemon, 1977; Revelle et al., 1980, AAAS, 1980). Although many of these have been focused on issues relating to climatic changes, several have also included research agendas for nonclimatic impacts. In fact, the general consensus seems to be that the first priority should be investigations of the direct biological effects of enhanced carbon dioxide levels rather than the propagation effects that may occur if and when the climate changes. The nature of potential climatic changes is still highly debatable, but it has been well-established that the atmospheric carbon dioxide content has increased 7% since systematic measurements were begun in 1958, and that it will in all likelihood continue to increase over the next several decades. These increases are likely to have direct biological effects.

Several other general conclusions have been reached about future research on carbon dioxide effects:

(1) Although a considerable amount of research has already been conducted (particularly on plant response), past experiments were not designed to answer questions about long-term global carbon dioxide enrichment.

(2) Further research efforts should be preceded by the development of an analytical approach by an interdisciplinary team of scientists. The atmosphere/earth system is quite complex, and the effects of increased carbon dioxide will touch the lives of all mankind in one way or the other. A truly integrated approach will require not only the interaction of physical and biological scientists, but of social scientists and policy makers as well.

(3) Long-term experiments need to be conducted to cover all stages of the life cycle of organisms under varying environmental conditions. To achieve this will require overcoming the common problem of being confined to short-term (i.e., one-year) budgets.

(4) An international effort is needed because the carbon dioxide issue is global in nature and because important human resources are available from many parts of the world. Establishing effective communication links among the various scientists involved with the carbon dioxide issue can greatly aid in our understanding of the complex issues commonly associated with this area of investigation.

Our recommendations for specific areas that should receive high priority are outlined in the pages that follow. The lists were developed from interviews with key scientists in the field, reviews of published research agendas, and our own evaluations of the possible contributions of various research areas to protecting human health and the environment.

Terrestrial Ecosystem Studies

(1) Long-term field studies are needed, as well as investigations in more controlled environments, to develop and validate a model for predicting plant growth responses at various carbon dioxide levels. Specifically, we need quantitative determinations of the effects of enhanced carbon dioxide levels on

   (a) Net carbon dioxide exchange

   (b) Stomatal response, transpiration, and water use efficiency

   (c) Photorespiration

   (d) Growth form, root/shoot ratios, growth rates, and maturity

   (e) Reproductive behavior, including phenology (the study of the timing of events in the life cycles of organisms), reproductive potential, and allocation of photosynthate

   (f) Nitrogen metabolism, including nitrogen fixation*

   (g) Yield response (in terms of both quantity and quality) of the economically used portion(s) of the plant.

Commercially important agronomic, range, and forestry species should be studied, with an emphasis on effects on the harvestable portion of the plant. The differing responses to elevated levels of C3 and C4 plants should be clarified. Important weed species and native plants representative of the various ecosystems should also be investigated, as should growth effects on decomposers. Data are especially needed on the life-cycle response of tropical tree species. Models that can predict plant response to enhanced carbon dioxide levels need to be developed and validated.

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* Wittwer (1980a) points out that the most important industrial input into agricultural productivity is nitrogen fertilizer. Little is known about how biological nitrogen fixation will respond to projected increases in carbon dioxide.

(2) The relationship of the effects of other environmental stresses to different levels of atmospheric carbon dioxide should be investigated. Specifically, the interactions of carbon dioxide levels and water and light availability, temperature stress, air pollutants, pests, and other plant diseases should be determined.

(3) Breeding programs should be developed to exploit the potential benefits of increased carbon dioxide levels. The principal benefits of enhanced carbon dioxide levels may be in greater photosynthetic produtivity and greater water-use efficiency both of which may result in increased yields of cultivated crops. Photosynthetic rate is known to be under genetic control, and it can be manipulated by breeding techniques. It is uncertain, however, whether an increase in sink size (demand for assimilates) or an increase in the source capabilities (amount of photosynthate being produced) would be more effective in increasing yield. Although photosynthetic rate per se may not be directly correlated with economic yield or dry matter accumulation (see Krenzer, 1974; Lemon, 1977; Fischer et al., 1981), we believe that studies that use both conventional breeding programs and modern methods of genetic manipulation should be undertaken to determine whether varieties of field crops can be developed that can make full use of higher carbon dioxide levels and use water more efficiently.

(4) We should investigate methods by which agricultural and silvicultural management practices could be altered to take better advantage of carbon dioxide fertilization. Some preliminary studies on the physical and physiological feasibility of carbon dioxide enrichment in field crops have been conducted by Harper et al. (1973a and 1973b) and Takami (1974).

(5) We need to obtain a better understanding of the role of the terrestrial ecosystem in global carbon cycling. To do so, detailed inventories of the global distribution of annual biomass production (cultivated crops, rangelands, forests) and of stored biomass (soils, forests, peats, man-made structures) are required. Satellite data should be useful in determining the changes in the extent and character of

land vegetation over time. To predict long-term responses to enhanced carbon dioxide levels, we will have to develop a framework that takes into consideration the pertinent environmental characteristics (e.g., carbon dioxide levels, water availability, wind), environmental processes (e.g., evaporation, convection, conduction), primary production (photosynthesis leading to allocation of products), secondary production (eventually leading to growth), and the population ecology of the species involved. Specific questions that must be answered include:

(a) Are major terrestrial biomes sources or sinks of carbon dioxide?

(b) How do enhanced levels of carbon dioxide affect the rate and total amount of biomass production?

(c) To what extent does human forest cutting influence the global carbon budget?

(d) How stable is net land photosynthesis and respiration in the northern and southern hemispheres?

(e) What roles do peat, organic soils, detritus, and humus play in the carbon dioxide cycle?

Aquatic Ecosystem Studies

High-priority areas of research on aquatic systems are listed as follows. Several of these recommendations directly or indirectly involve investigating the effects of changes in carbon dioxide concentrations on the pH of the water.

(1) It is necessary to establish the degree to which increased carbon dioxide levels could affect the skeleton formation of calcium-precipitating organisms.

(2) We should evaluate the potentiating effect of increased carbon dioxide levels on the toxicity of other pollutants.

(3) Evaluations of sensitive life stages of fish (e.g., Pacific herring) and invertebrates should be conducted to determine their effects on organisms' susceptibility to increased carbon dioxide levels. Long-term chronic studies should be performed on selected species to determine whether deleterious effects on growth and reproduction occur at the projected carbon dioxide concentrations.

(4) Similar screening studies should be undertaken to determine whether nephracalcinosis results in permanent kidney damage and impaired seawater adaptation in anadramous fish.

(5) We should evaluate potential effects of increased carbon dioxide on the composition of phytoplankton communities.

(6) We need to study the potential effects of enhanced carbon dioxide levels on amphibians. (These organisms are entirely aquatic at certain life stages.)

(7) We should experimentally evaluate carbon dioxide-induced succession in aquatic biota and determine the important factors controlling the species composition. This information will help us maximize production or minimize nuisance blooms.

Human Health Studies

We (and all those people we interviewed) believe that current information indicates that detectable human health effects would be highly unlikely, even among potentially sensitive populations. at carbon dioxide levels of 600 ppm. People are currently exposed to indoor concentrations of carbon dioxide that are in the range of 600 ppm, and the range of indoor exposure may double if the ambient level increases to 600 ppm. If EPA chooses to pursue further carbon dioxide-related health research in light of the long-term projected increases to levels greater than 600 ppm, SRI recommends the following.

(1) We should conduct animal studies, long-term as well as acute, of the effects on various blood and urine chemistries (including pH, arterial partial pressure of carbon dioxide, bicarbonate, Ca^{+2}, Mg^{+2} and PO_4^{-2}) of exposure to carbon dioxide at concentrations ranging from 600 to 2,000 ppm. Such studies should also look at physiological parameters, such as respiration rate and depth, and necropsies should include an examination of kidneys and lungs for evidence of calcification, and other ultrastructural changes (such as pneumocyte proliferation).

(2) Human studies should focus on respiratory parameters, blood and urine chemistries, and mineral balance (including regulatory hormones such as parathyroid hormone) during chronic exposure to carbon dioxide at low levels (600-2,000 ppm). Such studies should, if possible, include not only healthy individuals, but also those with respiratory impairment or renal damage and other relevant conditions, such as disturbances of calcium metabolism.

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APPENDIX A

Appendix A

PLANT RESPONSES TO ENHANCED ATMOSPHERIC CARBON DIOXIDE LEVELS

This appendix presents tabulated data on the responses of vegetables, flowers, field crops, and woody species to elevated levels of atmospheric carbon dioxide.

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
VEGETABLES[a]				
Bean	300; 1,000	Elevated levels generally promoted greater root growth both in the presence and in the absence of growth substances.	Plants grown in a culture root media solution	Tognoni et al. 1967
Cabbage (Chinese)	50,000	Enhanced bud pollination was observed in certain self-incompatible inbred lines.	Exposure duration: 2 hours	Lee, 1979
Cucumber	320; 1,300	Enriched air resulted in doubling the photosynthetic rate.	Fick's diffusion law is modified to predict net photosynthesis	Gaastra, 1959
Cucumber	Controls: 100-150 (morning) to 1,500-5,000 (shortly before sunrise) Enhanced level: 10,000	Treated plants developed more quickly, produced fruits earlier, and yielded 45% more fruit than controls.	Exposure duration: 498 daylight hours over 61 days; plants grown in low plastic tunnels in a subtropical climate	Enoch et al. 1970
Cucumber	Ambient; 1,300	Enhanced air increased early marketable yields by 18% and resulted in doubling the photosynthetic rate.	Exposure duration: every morning during winter until harvest	Ito, 1972
Cucumber	350; 400; 1,200	Accelerated growth conditions resulted in test plants weighing up to 10 times as much as controls.	Exposure duration: 15 days; temperature, light, humidity, and nutrients also altered	Krizek, et al. 1974
Kidney bean	400; 800; 1,200	Enhanced levels produced significantly greater fresh and dry weights of leaves and higher carbohydrate levels; however, no statistical difference was found in the fresh or dry weights of those plants grown under 800 ppm and those under 1,200 ppm.	Study conducted in growth chambers	Knecht and O'Leary, 1972

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[a] All vegetable experiments were conducted under greenhouse, laboratory, or growth chamber conditions.

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Lettuce	125-500; 300-2,000	Yields of plants grown in enriched air increased 30-70% on a fresh weight basis.	Exposure: during daylight hours until harvest	Wittwer and Robb, 1964
Lettuce	Controls: 100-150 (morning) to 1,500-5,000 (shortly before sunrise) Enhanced level: 10,000	Treated plants yielded 15% more than controls.	Exposure duration: 498 daylight hours over 61 days; plants grown in low plastic tunnels in a subtropical climate	Enoch et al., 1970
Lettuce	350; 2,000	Depending on light intensity and relative humidity levels, the enriched levels increased the dry weight from 55 to 88% at 28 days after seedling emergence. Tipburn development occurred 1 to 2 days earlier with carbon dioxide enrichment; however, tipburn was usually encouraged by any factor that increased the growth rate of the plants.	Growth chamber study	Read, 1972
Lettuce	350; 400; 1,200	Accelerated growth conditions resulted in test plants weighing up to 10 times as much as controls.	Exposure duration: 15 days; temperature, light, humidity, and nutrients also altered	Krizek et al., 1974
Lettuce	Ambient, 3 times ambient (about 900)	Enriched autumn crops, provided with higher daytime temperatures, matured 2 weeks sooner than the ambient crops (7 vs. 9 weeks); enriched plants showed 8-50% greater yield (grams per plant).	Author was unable to breed cultivars which were more efficient in carbon dioxide utilization; breeding experiments were conducted for 7 years	Smith, 1977
Pea (dwarf)	90-520	Photosynthesis increased up to 450 ppm, but was little affected above this level.	Laboratory experiment	Hellmuth, 1971
Potatoe	Enhanced levels (45% carbon dioxide at root zone)	Plants grown in enhanced levels showed a significant increase in overall dry weight and tuberization; they also showed an increase in their photosynthetic rate and a general suppression of their photorespiratory rate.	Exposure duration: 12 hours	Arteca et al. 1979; Arteca and Poovaiah, 1980
Radish	400; 1,200	Growth of both plant tops and roots was increased under enhanced levels; root/shoot ratio increased by more than a factor of 2.	Experiments conducted in growth chambers	Knecht, 1975
Radish	50,000	In certain self-incompatible, inbred lines, the gas treatment enhanced bud pollination; in other lines, seed production was not increased.	Exposure duration: 2 hours	Lee, 1979
Spinach	320; 1,300	Enriched air resulted in doubling the photosynthetic rate.	Laboratory experiment, but leaves were attached to plant	Gaastra, 1959

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Sweet pepper	Controls: 100-150 (morning) to 1,500-5,000 (shortly before sunrise) Enhanced level: 10,000	Treated plants set more fruit and gave a 20% yield increase.	Exposure duration: 498 daylight hours over 61 days; plants grown in low plastic tunnels in a subtropical climate	Enoch et al., 1970
Tomato	320; 1,300	Enriched air doubled the photosynthetic rate.	Laboratory experiment, but leaves were attached to plant	Gaastra, 1959
Tomato	125-500; 800-2,000	Yields of marketable fruit grown in enriched air increased from 25 to 70%, with a mean of 43%; fruit size also increased.	Exposure: during daylight hours until harvest	Wittwer and Robb, 1964
Tomato	300; 1,000	Both in the absence and the presence of growth substances, enhanced levels generally promoted greater root growth and produced an increase in the root to top dry weight ratios.	Growth conditions: culture root media solution with growth substances	Tognoni et al., 1967
Tomato	Ambient; 1,000	Enriched air increased photosynthetic rate 3 times.	Grown under different light conditions	Bishop and Whittingham, 1968
Tomato	Ambient; 3-5 times ambient (about 900-1,500)	Total yields (pounds/plant) increased 5-25% at the enhanced levels.	Exposure duration: January and February	Kretchman and Howlett, 1969
Tomato	300; 600; 1,200; 2,300	Increasing the carbon dioxide level from 300 to 600 ppm promoted phosphorous and nitrogen uptake rates. At 1,200 and 2,300 ppm, phosphorous uptake was inhibited and abnormal morphological changes occurred.	A walk-in type of growth chamber was used	Ghoddousi, 1970
Tomato	300; 3,000 (10 times ambient)	Dry weight increased by 200%.	Exposure duration: 16 days	Guminska and Osmelak, 1971
Tomato	350; 1,000; 1,500; 2,200; 3,200; 5,000	Maximum photosynthetic rate occurred at 1,000 ppm.	Laboratory study	Madsen, 1971
Tomato	Ambient; 600-1,200	Spring crop under enhanced levels showed 5-28% yield increase and no reduction in quality; no significant response was shown for enriched fall crops.	Exposure duration: daylight hours during spring and fall	Bauerle and Kretchman, 1972
Tomato	Ambient; enriched (about 900)	Enrichment increased the number of fruits of the early crop by 90% and of the total crop by 30%; it also advanced the date of flowering.	Exposure: during daylight hours	Calvert, 1972
Tomato	Ambient; 1,300	Enriched air increased early marketable yields by 15%; effects were most noticeable when gas was applied to the younger stages of the plants.	Exposure duration: every morning during winter throughout the growing period	Ito, 1972

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Tomato	Ambient; 600-1,200	Plants grown in enriched air had 4-12% more fruit set per plant and a higher percentage of No. 1 grade fruit.	Exposure duration: daylight hours during spring	Bauerle and Kretchman, 1973
Tomato	350; 400; 1,200	Accelerated growth conditions resulted in test plants weighing up to 25 times as much as controls.	Exposure duration: 15 days; temperature, light, humidity, and nutrients also altered	Krizek et al., 1974
Tomato	Ambient; 600; 1,000; 1,400	Plants grown under enhanced levels up to 1,000 ppm showed 35% increased yields, but increases up to 1,400 were generally insignificant.	Exposure: in fall	Calvert and Slack, 1975
Tomato	300; 650; 1,000; 1,500; 2,200; 3,200	Plants were able to use the gas up to 2,000 ppm.	Utilization was heavily influenced by light intensity	Madsen, 1975
Tomato	Ambient; 1,000-1,500	Enhanced levels produced a significant increase in plant height, number of fruiting clusters, and shoot fresh weight; fruit yield was increased and fruit quality was improved.	Performed in greenhouses at the Ohio Agricultural Research and Development Center	Carter, 1978
Tomato	Ambient; 900	Under enhanced conditions, plants flowered earlier and produced 30% more marketable fruit.	Data for spring crop in greenhouses	Hicklenton and Jolliffe, 1978
Tomato	Ambient; 650; 1,000; 1,350	Plants grown at 650 and 1,000 ppm had 17 and 48% greater yields than the controls; at the standard nutrient level, plants yielded 64 and 63% more than the controls at 1,000 ppm and 1,350 ppm, and at the high nutrient level, 35 and 37% more.	Using ventilated and unventilated greenhouses	Kimball and Mitchell 1979
Tomato	Ambient; 1,000; 5,000	Relative growth rates were greatest at 1,000 ppm and less at 300 and 5,000 ppm.	Enrichment to concentrations above 1,000 ppm may be detrimental	Hicklenton and Jolliffe, 1980
FLOWERS				
Carnation (red gayety)	200; 350; 550	At enhanced levels, plants showed increases in dry matter and flower yield and decreases in mean stem length of flowers; plants also bloomed 2 weeks earlier at enhanced levels.	Greenhouse study	Goldsberry, 1963
Carnation	Ambient, 600; 900; 1,500	Enhanced levels did not statistically affect production; however, the weight of the flower stems was increased at these levels.	Greenhouse study	Koths, 1967
Chrysanthemum	Ambient; 1,500; 4,000	Flower size, stem length, and dry weight increased in the enriched air.	Greenhouse study	Lindstrom, 1968

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Chrysanthemum	325; 900; 1,500	Final plant weight increased over the range of 325-900 ppm; little further increase occurred at 1,500 ppm; enriched levels resulted in larger leaf areas, higher water content, and slightly faster flower development.	Exposure duration: from 1 hour before lights on until lights off	Hughes and Cockshull, 1972
Pharbitis nil choisy	Low levels: 300; 1,000 High levels: 10,000; 50,000	At low levels, short day photoperiods caused rapid flowering while plants in long day conditions remained vegetative; at enhanced levels, flower buds were developed under both the short and long day photoperiods.	Greenhouse-grown tomatoes were transferred to growth chambers for the study	Hicklenton and Jolliffe, 1980
Rose (greenhouse)	100-500; 700-1,300; 1,500-2,500	At enriched levels, the number of flowering stems and lateral buds, fresh weight, and stem length were greater for hybrid tea and floribunda roses; floribundas also had lower nonflowering percentages.	Exposure duration: for at least half of the daylight hours from November to May	Mattson and Widmer, 1971
Rose (3 varieties)	Ambient; 700; 2,500	High levels produced 24% more flowers.	Greenhouse study	Hanan, 1973
Rose	Ambient; 1,000	Enrichment caused 23% more marketable blooms.	Exposure: during winter	Hand and Cockshull, 1975
Snapdragon (2 varieties)	300; 600	At high light intensities, the optimum carbon dioxide saturation was 500-600 ppm; at low light levels, the optimum was 350 ppm.	Greenhouse study	Hedley and Harvey, 1975
FIELD CROPS				
Barley	300; 1,000; 3,300	Increasing the gas concentration to 1,000 ppm increased the total dry weight by 50%; a further increase to 3,300 ppm increased dry weight slightly more.	Growth chamber study	Ford and Thorne, 1967
Barley	200; 400; 600; 800	Stomata were less prone to close as gas concentrations increased.	Laboratory/greenhouse study	Akita and Moss, 1972
Corn	Ambient-510	Enhanced levels resulted in increased carbon assimilation at high light intensities; small increases in the gas caused large decreases in stomatal aperture and transpiration.	Field measurements	Moss et al., 1961
Corn	300; 1,000, 3,300	Net assimilation rates at 1,000 and 3,300 ppm were about 20 and 30% greater than at 300 ppm; enhanced levels also produced taller plants.	Growth chamber study	Ford and Thorne, 1967
Corn	300; 1,000	Floral initiation was slightly delayed at the higher level.	Laboratory/greenhouse study	Hesketh and Hellmers, 1973

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Corn	Ambient-1,000	Carbon dioxide enrichment would not be practical under most natural field and crop conditions because of rapid gaseous exchange between the canopy air and the atmosphere.	Field experiment in August and September in New York	Allen et al., 1974, Allen, 1975
Corn	Ambient; elevated	At elevated levels, photosynthesis increased 40-65%.	Laboratory study	Wittwer, 1974
Corn	315; 350; 400	At elevated levels, net photosynthesis in the field is expected to increase only about 4-8%.	SPAM (a soil-plant atmosphere model) was used to simulate field conditions	Lister and Lemon, 1976
Corn	Ambient	For 64 inbred corn lines nonsignificant correlations were found between carbon dioxide exchange rates (CER) and yield traits, indicating that CER was not the primary factor limiting yield; rather, dry matter yield was limited by amount of leaf area and by traits associated with efficient use of light energy.	Field plots	Crosbie et al., 1978
Corn	300; 1,000	With enhanced carbon dioxide and normal oxygen (21%), the dry weight increased 16-21%; under low oxygen (6%), the dry weight increased 11-17% at the enhanced carbon dioxide level. Decreasing the oxygen concentration from 21% to 6% resulted in a 1-4% increase in dry weight at both carbon dioxide levels.	Greenhouse/growth chamber study; plants sampled after 5 days exposure	Imai and Murata, 1979a
Corn	300; 1,000	At the enhanced level with high light intensity, plants increased in dry weight by 12-22%; at a low light intensity, they increased 10-15%.	Greenhouse/growth chamber studies; plants sampled after 5 days of exposure	Imai and Murata, 1979b
Corn	50-600	At low light intensity, net photosynthesis increased at carbon dioxide levels up to about 400 ppm; at high light intensity, net photosynthesis increased at levels up to about 600 ppm.	Closed chamber at crop canopy	Baker and Lambert, 1980
Corn	350; 600; 1,000	Dry matter production 45 days after planting was least at 1,000 ppm and was almost the same at 350 and 600 ppm; the dry weight at 1,000 ppm was 12% less than 12 days after planting, the reverse trends had been observed, those at 1,000 ppm having 21% greater dry weights than those growing at 350 ppm.	Growth chamber study	Patterson and Flint, 1980

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Corn (Golden Bantam)	535; 735; 935	Net carbon dioxide uptake remained constant or slightly decreased with increasing carbon dioxide levels.	Field study using open top cylinders	Rogers and Bingham, 1981
Cotton	200-2,000	Linear increases in photosynthesis up to values of 600-800 ppm; above these levels, there appeared to be effective carbon dioxide saturation.	Leaf chamber experiment	Bierhuizen and Slatyer, 1964
Cotton	100-600	Increasing carbon dioxide levels resulted in linear increases in apparent photosynthesis.	Semiclosed system in the laboratory	Baker, 1965
Cotton	Ambient to 450-500	Daily net photosynthate production increased by an estimated 35% at the enhanced levels.	Field study	Harper et al., 1973a
Cotton	Ambient; elevated	At elevated levels photosynthesis increased by 50-60%.	Laboratory study	Wittwer, 1974
Cotton	50-600	Linear increases in net photosynthesis and linear decreases in transpiration occurred at elevated levels; yield increases ranging from 14-38% would be expected at enhanced carbon dioxide levels depending on several variables (e.g., light, temperature, pest pressure).	A dynamic crop simulation model (a process-oriented model) was developed based on results from canopy photosynthesis experiments	Baker and Lambert, 1980
Field bean	Ambient-2,200 (0.22%)	Enhanced levels resulted in 30% more seeds per plant.	Field study; gas applied 8 hours/day for 3 weeks beginning at onset of seed development	Day and Roughley, 1979
Kale	300-1,000	At 1,000 ppm, the total dry weight increased by 50%; a further increase to 3,300 ppm increased dry weight slightly more.	Growth chamber	Ford and Thorne, 1967
Millet	300; 1,000	Under enhanced carbon dioxide levels and normal oxygen conditions, the dry weight increased 27-32%; under low oxygen conditions (6%), the dry weight increased 7-21% at the enhanced carbon dioxide level; decreasing the oxygen concentration from 21 to 6% resulted in a 3-22% decrease in dry weight at 1,000 ppm carbon dioxide and a 1-2% increase at 300 ppm.	Growth chamber study; plants sampled after 5 days exposure	Imai and Murata, 1979a
Millet	300; 1,000	Under the enhanced level and high light intensity, plants increased in dry weight by 23-30%; at a low light intensity, they increased 13-30%.	Greenhouse/growth chamber studies; plants sampled after 5 days of exposure	Imai and Murata, 1979b
Rice	1,000-2,400	Enriched levels produced a 19-650% increase in yield.	Greenhouse/growth chamber study	Riley and Hodges, 1969

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Rice	900 ± 200	Enriched levels increased yields both before and after flowering.	Chambers in the field were used; treatments were for 30 days before or after flowering	Cock and Yoshida, 1973
Rice	900 ± 200	Enriched levels for 33 days before flowering increased grain yield by 30% over the control; 30 days enrichment after flowering increased grain yield by 10% over the control.	Open top chambers in the field were used	Yoshida, 1973
Rice	Ambient; elevated	Rate of photosynthesis increased 80-280% at elevated levels.	Greenhouse/laboratory study	Wittwer, 1974
Rice	Ambient; elevated (99.8%)	Carbon dioxide gas in the root zone significantly reduced seedling growth.	Nutrient culture technique was used; exposure duration: 10 days	Niranjan and Mikkelsen, 1977
Rice	300; 1,000	Under enhanced carbon dioxide levels and normal oxygen conditions, the dry weight increased 35-47%; under low oxygen conditions, dry weights increased 4-18%; decreasing the oxygen from 21% to 6% resulted in a 22-30% increase of dry weight at 300 ppm carbon dioxide and a -2 to +4% change at 1,000 ppm .	Growth chamber study; plants sampled 5 days after exposure	Imai and Murata, 1979a
Rice	300; 1,000	At the enhanced level with high light intensity, plants increased in dry weight by 20-52%; at a low light intensity, they increased 24-48%.	Greenhouse/growth chamber studies; plants sampled after 5 days exposure	Imai and Murata, 1979b
Sorghum	Ambient; 1,000-2,000	Yields increased 168-232% at enhanced levels.	Greenhouse/growth chamber conditions	Riley and Hodges, 1969
Soybean	350; 1,350	Seed yields increased 40-57% at the enhanced level.	Exposure was in chambers in greenhouse from seedling to maturity	Cooper and Brun, 1967
Soybean	Ambient; 1,000-2,000	Yields increased 500-550% at enhanced levels.	Greenhouse/growth chamber conditions	Riley and Hodges, 1969
Soybean (3 varieties)	300-600	Enhanced levels increased the mean daily apparent photosynthesis rate by 53-84% and reduced transpiration rates.	Measured in a closed canopy	Egli et al., 1970 Egli, 1969
Soybean	300; 600; 1,200; 2,300	Increasing the carbon dioxide level from 300 to 600 ppm promoted phosphorous and nitrogen uptake rates. At 1,200 and 2,300 ppm, phosphorous uptake was inhibited but the plants were not visually affected.	A walk-in type of growth chamber was used	Ghoddousi, 1970

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Soybean	Ambient; 1,200 ± 150	Enrichment during the vegetative stage had no effect; enrichment during flowering did not affect yield but did increase dry weights and pod numbers and decreased seed size; enrichment during pod-filling had no effect on vegetative parameters, but caused a marked increase in pod weight (32%) and seed yield (27%); continuous enrichment caused highly significant increases in vegetative parameters and in seed yield (43%).	Field study; exposure for 5 weeks corresponding to the vegetative, flowering, and pod-filling stages of development; also, one treatment included continuous exposure from June 16 to September 27	Hardman and Brun, 1971
Soybean (4 varieties)	Ambient; 1,300	Enhanced levels resulted in a small increase in bean yield in 3 of the 4 varieties tested; the fourth variety showed a slight decrease in yield.	Growth chamber study; exposure for 10 hours a day from 12 days post-flowering to maturity	Maddox, 1974
Soybean	Ambient; elevated	Elevated levels increased photosynthesis by 40-87%.	Greenhouse/laboratory study	Wittwer, 1974
Soybean	300; 1,000	Depending on the temperature regime, dry weights increased by less than 10% to more than 280% at the enhanced level.	Studies were in growth chambers (phytotrons)	Hofstra and Hesketh, 1975
Soybean	300; 1,000	Under enhanced carbon dioxide levels and normal oxygen conditions, the dry weight increased 35-70%; under low oxygen conditions, dry weights increased 15-48%; decreasing the oxygen from 21% to 6% resulted in a 21-29% increase in dry weight at 300 ppm carbon dioxide and a 2-9% increase in dry weight at 1,000 ppm carbon dioxide.	Greenhouse/growth chamber study; plants sampled 5 days after exposure	Imai and Murata, 1979a
Soybean	300; 1,000	At the enhanced level with high light intensity, plants increased in dry weight by 23-73%; at a low light intensity, they increased 23-52%.	Greenhouse/growth chamber studies; plants sampled after 5 days exposure	Imai and Murata, 1979b
Soybean	350; 600; 1,000	At 600 ppm, dry weight increased 23%; at 1,000 ppm, dry weight increased 72%; 45 days after planting.	Growth chamber study (phytotron)	Patterson and Flint, 1980
Soybean	350; 1,000	Dry weights were increased at the enhanced level; the photosynthetic rate of high sink plants (with many pods) was higher than that for low sink plants (with few pods).	Growth chamber study	Clough et al., 1981
Soybean (Ransom)	535; 735; 935	Enhanced levels increased net carbon dioxide uptake and gross photosynthesis; stomatal conductance was decreased.	Field study using open-top cylinders	Rogers and Bingham, 1981
Sugar beet	300; 1,000	Enhanced level increased total dry weight by 50%.	Growth chamber study	Ford and Thorne, 1967

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Sugar beet	300-500	Photosynthesis increased linearly to increased carbon dioxide concentrations.	Laboratory study	Nevins and Loomis, 1970
Sugar beet	Ambient; elevated	Elevated levels increased photosynthesis by 40-87%.	Greenhouse/laboratory study	Wittwer, 1974
Sugar beet	315; 400	Depending on diffuse radiation levels, the enhanced level increased net photosynthesis 12-20%.	SPAM was used to simulate field conditions	Lister and Lemon, 1976
Sunflower	Ambient; 500-5,000	Enhanced levels increased yields 144-550%.	Greenhouse/growth chamber study	Fock et al., 1971
Sunflower	Ambient; elevated	Elevated levels increased photosynthesis 100-160%.	Greenhouse/laboratory study	Wittwer, 1974
Tobacco	300-1,000	Net photosynthesis increased with carbon dioxide concentration up to 1,000 ppm.	Greenhouse/laboratory study	Hesketh, 1963
Tobacco	400; 1,000	Enrichment had little effect on plant growth beyond seedling development, although enrichment did enhance the growth rates during seedling culture.	Growth chamber study	Thomas et al., 1975
Tobacco	400; 1,000	The net carbon dioxide exchange rates were greater at 400 than at 1,000 ppm.	Plants grown in controlled-environment rooms	Raper and Peedin, 1978
Wheat	Ambient; 1,200-2,400	Enhanced levels increased yields 100-138%.	Greenhouse/growth chamber study	Riley and Hodges, 1969
Wheat (hard, red spring, Era and 8037)	325 ± 50; 600 ± 100	Grain yield increased by up to 38% or was unaffected depending on the temperature regime and the developmental stage the plants were in at the time of exposure.	Field experiments (at St. Paul, Minnesota) and growth chamber studies	Krenzer, 1974 Krenzer and Moss, 1975
Wheat (dwarf spring, Yecora 70)	Ambient; 750	Grain yield was either unaffected or increased by up to 23%, generally depending on the timing of the gas fertilization.	Irrigated field experiment in northwest Mexico; enclosed small areas of crops (1 to 2 m2) in transparent chambers; experiments conducted for 3 winter cropping cycles (1970-1973)	Fischer and M., 1976
Wheat	Ambient (280-300); Ambient +200 ± 20; Ambient -150 ± 20	Response of yield to carbon dioxide enrichment corresponded to 0.25% per ppm; growth response to enhanced levels was greater under low than under high radiation regimes.	Growth chamber study under winter and summer light conditions	Gifford, 1977
Wheat	Ambient; Ambient + 250	The less water was made available, the smaller the absolute response of grain yield to carbon dioxide enrichment, but the greater was the response relative to the control yield; the absolute yield enhancement was equivalent to 5-13 kg per hectare per 1-2 ppm increment of atmospheric carbon dioxide concentration.	Growth chamber study under 4 levels of growth-restricting water supply	Gifford, 1979

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Wheat	Ambient; 500	Yields increased 59% under enhanced levels; largest relative yield was during the most severe environmental stress conditions.	Data from a yield model for winter wheat which uses daily meteorological and physiological inputs	Kanemasu, 1980
Wheat (semi-dwarf, spring)	350; 1,000	Generally, plants grown at enhanced carbon dioxide levels and water stress conditions had a grain yield and total dry matter production equal to those of the unstressed plants grown at low levels of carbon dioxide.	Growth chamber study (phytotron) using 2 water stress regimes	Sionit et al., 1980
WOODY SPECIES				
Apple	Ambient; 900-1,200 (3-4 times normal concentration)	Enhanced levels increased shoot growth.	Growth chamber studies, but comparisons made with trees growing out of doors	Hansen, 1975
Birch (seedlings)	400; 2,000	Stimulatory effects were greatest at 2,000 ppm; significant increases in node number, stem length, branching, and leaf area were noted.	Growth chamber/greenhouse conditions	Krizek et al., 1969, 1971
Cottonwood (100-120 cm high)	Ambient - 1,000	Maximum net photosynthesis occurred at 1,000 ppm.	Gas exchange rates measured in a semiclosed infrared gas analysis system	Regehr, 1975
Crabapple (seedlings)	400; 2,000	Stimulatory effects were greatest at 2,000 ppm; significant increases in node number, stem length, branching, and leaf area were noted.	Growth chamber/greenhouse conditions	Krizek et al., 1969
Crabapple (seedlings)	Ambient; 3,000	Enriched levels resulted in a significant increase in height, number of nodes, and the number and length of lateral shoots.	Growth chamber/greenhouse conditions	Zimmerman et al., 1970
Douglas fir (seedlings)	350-500	Increased levels resulted in increased photosynthetic rates.	Laboratory study	Fry, 1965
Grapevine	300; 950; 1,200-1,300	At 950 ppm, net photosynthesis increased and photorespiration appeared to decrease; at 1,200-1,300 ppm, plants survived better than controls under high heat and virus stress.	Laboratory study	Kriedemann et al., 1976
Pine, coulter, knobcone (seedlings)	50-450	Enhanced levels increased net photosynthesis.	Laboratory study	Hurt and Wright, 1976
Pine, jack and Scotch (seedlings)	300; 900-1,500 (3- to 5-fold enrichment)	Enhanced levels resulted in a 30-80% increase in dry weight.	Greenhouse experiment	Yeatman, 1970

Plant Species	Carbon Dioxide Levels (ppm)	Plant Response	Notes	Source
Pine, loblolly	535; 735; 935	Enhanced levels resulted in growth enhancement.	Field study with open top cylinders	Rogers and Bingham, 1981
Pine, ponderosa (seedlings)	300-1,200	Plants grew larger at 1,200 ppm and had significantly different growth form.	Laboratory study	Tinus, 1972
Pine, ponderosa	Ambient, ambient + 150	Enhanced levels resulted in an 84% increase in net photosynthesis and compensated for reduction of 50% in light intensity.	Field study in the San Bernardino Mountains of Southern California, June-October	Green and Wright, 1977
Pine, white (seedlings)	300 ± 100; 1,000 ± 200	Height, stem diameter, and crown widths twice as large grown at 1,000 ppm as at 300 ppm.	Growth chamber study	Funsch et al., 1970
Spruce, blue (seedlings)	300; 1,200	Enhanced level produced larger seedlings that had significantly different growth forms.	Greenhouse experiment	Tinus, 1972
Spruce, Norway and white (seedlings)	300; 900-1,500 (3- to 5-fold enrichment)	Enhanced levels resulted in a 30-80% increase in dry weight.	Greenhouse experiment	Yeatman, 1970
Sweetgum	535; 735; 935	Enhanced levels increased net carbon dioxide uptake and decreased stomatal conductance.	Field experiment with open-top cylinders	Rogers and Bingham, 1981
Walnut, black (seedlings)	325; 1,500	Enhanced levels increased dry weight of the seedlings.	Greenhouse experiment	Tinus, 1976

Appendix B

CARBON DIOXIDE CONTROL OPTIONS WORKSHOP

TO: Carbon Dioxide Workshop Participants

FROM: Marilyn K. Bland

SUBJECT: Carbon Dioxide Control Options Workshop

TIME/PLACE: Wednesday, November 11, 1981, 1-5 PM
Ishizaka Conference Room (IS 117)
International Building, SRI International
333 Ravenswood Avenue, Menlo Park, California

PURPOSE: To identify and evaluate carbon dioxide control technologies and strategies

REFERENCE MATERIALS: Enclosed are 50 abstracts of articles relating to atmospheric carbon dioxide control or the carbon cycle. Please scan these abstracts before the workshop. Complete articles are on file in my office for those interested.

SCHEDULE:

1:00	Introductions, Overview
1:20	Identifying Carbon Dioxide Control Methods
3:00	Break
3:15	Evaluating the Identified Methods
5:00	Workshop Concludes

Participants:*

Howard Bailey, Program Director, Toxicology Laboratory
Marilyn Bland, Senior Ecologist
Tom Boyce, Director, Energy Center
Richard Brodzinsky, Atmospheric Chemist
Steve Brown, Director, Center of Health and Environmental Research
Dick Carlson, Senior Regional Economist
Charles Greene, Manager, Synthetic Fuels Program
Nick Korens, Manager, Energy Technology Economics Program
John Laurmann, Professor, Division of Applied Mechanics (Stanford University)
Michael Lipsett, Senior Policy Analyst
Art McGee, Manager, Business Opportunities in Coal Program
Mike Miller, Technical Manager, Environmental Control Systems Department, Coal Combustion Systems Division (Electric Power Research Institute)
Konrad Semrau, Senior Chemical Engineer

*All from SRI International except where designated

1. Albanese, A.S., and M. Steinberg, Environmental Control Technology for Atmospheric Carbon Dioxide, Final Report, prepared by Brookhaven National Laboratory for the U.S. Department of Energy's Carbon Dioxide Effects Research and Assessment Program, Report 006, DOE/EV-0079, May 1980.

Three potential carbon dioxide control points are considered: the atmosphere itself; surface waters of the ocean; and the stacks of fossil fuel plants. Control of only the last is considered feasible, largely because of the relatively lower energy requirements associated with these options.

The most effective carbon dioxide removal process from flue gas appears to be MEA (monoethanolamine); however, the use of MEA will significantly reduce the overall power plant efficiency. Using the MEA technology for 50% carbon dioxide removal, it is estimated that the power generation efficiency of a conventional coal fired plant would be reduced from 34% to about 25%. The resulting cost of power generation would be expected to double. For 90% carbon dioxide removal, the cost of power generation increases by a factor of 4 to 7.

Four ways of disposing of captured carbon dioxide are considered: (1) injection in the deep ocean; (2) terrestrial burial; (3) storage in plants and trees; and (4) extraterrestrial disposal. Deep ocean storage (gaseous disposal by a deep ocean pipeline) appears to be the most promising. Extraterrestrial disposal and several of the terrestrial burial options noted (e.g., storage in abandoned mine shafts, fixation in natural clays, and injection of carbon dioxide into depleted oil wells for enhanced oil recovery) were considered impracticable, either because of the large quantities of carbon dioxide accumulated or because of the numerous uncertainties involved in their implementation.

Two major problems could occur from using fast-growing, long-lived trees for carbon dioxide disposal that are left unharvested and/or short-lived plants that are converted to humus or allowed to accumulate in artificial peat bogs: (1) these actions would be limited by fertilizer supplies, and (2) additional carbon dioxide would be generated by reforestation activities and fertilizer production.

Other control methods identified, but not considered, in this study include the substitution of nonfossil energy sources, such as nuclear or solar, and recovering and converting carbon dioxide to synthetic liquid and gaseous carbonaceous fuels using a nonfossil energy source. The report also notes that although a number of commercial carbon dioxide products can be made, (e.g., dry ice), the quantity of these products produced and consumed yearly is extremely small in comparison to the huge quantities of fossil carbon dioxide emitted.

2. Bach, W., "The Carbon Dioxide Problem. Possible Solutions through Technical Counterregulation," Umsch. Wissensch. Techn. 78: 117-118, 1978.

A variety of measures for the reduction of carbon dioxide is presented. One promising approach, according to the author, is to work out a worldwide energy mix that can counteract a temperature increase.

3. Baes, C.F., et al. (eds.), "Collection, Disposal, and Storage of Carbon Dioxide." 27 pp. in International Workshop on the Energy/Climate Interactions, March 13, 1980, Munster, F.R. Germany, NTIS, CONF 800309-4, 1980.

This article estimates that to scrub carbon dioxide from the stack gas of a coal-fired plant by the most efficient means available would require about 43% of the combustion energy of the coal. Although appreciable improvement might be realized by burning the coal in pure oxygen, any method of recovery will use a substantial fraction of the energy content of the fuel. The best option for disposal is in the ocean, in the form of a negatively buoyant plume of concentrated solution that would carry the carbon dioxide to deep water where it would be stored for many hundreds of years. Alternatively, liquid carbon dioxide could be injected at great depths, or blocks of the solid hydrate or dry ice might be released at the ocean surface. The authors suggest that the most efficient option for the future might be floating power stations that would use cold, deep seawater both for condensor cooling and carbon dioxide disposal. Depleted oil and gas fields could be used as a near-term storage option. Storage as buried biomass or as a solid near the South Pole is considered to be the least desirable option .

4. Bassham, J.A., "Increasing Crop Production Through More Controlled Photosynthesis," Science 197: 630-638, August 1977.

In discussing biosynthetic strategies for increasing crop yields this paper concludes that an obvious environmental variable that has not yet been exploited (except for limited use in greenhouses) is carbon dioxide enrichment. The author suggests a scheme for energy and protein production by covered agriculture. Alfalfa would be grown under transparent cover year-round; carbon dioxide obtained from flue gases from fossil fuel power plants would be added. Greater photosynthetic efficiency would be achieved (and thus most likely higher crop yields) by reducing photorespiration as a result of the increased carbon dioxide levels. Bassham points out, however, that serious economic and engineering problems are associated with this scheme.

5. Botkin, D.B., "Forests, Lakes, and the Anthropogenic Production of Carbon Dioxide," Bioscience 27: 325-331, May 1977.

The biota of the earth is intimately involved in the global carbon cycle. The metabolic activities of the biota involve a substantial carbon flux with respect to carbon pool sizes. One of the questions this paper examines is whether terrestrial biota might represent an important sink for carbon dioxide. It concludes that extreme carbon dioxide enrichment may have a significant effect on primary production and could increase the standing crop of forests. Such an increase could potentially represent a short-term carbon sink. However, this potential is not and probably will not be met, because man's activities are rapidly reducing this biomass. Botkin also notes that plants growing under natural conditions are growth limited by temperature, moisture, or soil nutrients. If these limitations are severe, an increase in carbon dioxide would have only negligible effects.

6. Breuer, G., Air in Danger, 189 pp., Cambridge University Press, Cambridge, England 1980.

This book describes how our atmosphere has developed throughout thousands of millions of years and analyzes to what extent humans are disturbing it and specifically, the environmental implications of carbon dioxide increases in the atmosphere.

The basic carbon cycle must be understood before meaningful energy policies can be recommended. We do not yet have good estimates of how much biomass exists in the world and how fast it is changing.

Four carbon reservoirs are described:

(1) In plants that make and use the carbohydrates necessary to meet their own energy requirements, the carbon residence time varies between fractions of a second to a day because of their respiring process. Thus natural variations of carbon dioxide at tree-top level in a forest may vary from 305 ppm during sunny afternoons to 400 ppm at night. (These measurements were taken in the late 1960s when the average abundance of carbon dioxide was 320 ppm).

(2) Short-lived biological products (provided they do not contribute to humus formation) include crops, grass, flowers, foliage, fruits, seeds, and bulbs. Most animals can also be placed in this reservoir, although the total mass of all animals that live on land amounts to only one-thousandth of land vegetation. The residence time-scale of the carbon is of the order of weeks to years.

(3) Wood of living trees and humus, remnants of plants undergoing biological decomposition, long-lived species of animals, and the human race can also be placed in this reservoir, which holds more than 90% of the living substance and nearly all of the decomposing substance on land. The carbon is fixed for tens to hundreds, even thousands of years. It amounts to at least 2 to 3 times the carbon stored in atmospheric carbon dioxide.

(4) Remnants of plants and animals that are buried in sediments and constitute by far the greatest reservoir. Taking part in long-term geological cycles, carbon generally remains in this reservoior for several hundred million years.

Breuer notes that the composition of the atmosphere does not depend on the rate at which the carbon passes through a reservoir but rather on the total mass fixed within that reservoir.

Several alternative ways are discussed for controlling carbon dioxide, including:

(1) Switching to a plutonium economy with its associated security and environmental problems

(2) Imposing a zero growth rate with respect to energy use--a completely unrealistic approach in view of the energy demands of the Third World countries and the projected population growth rate of the world ("In the countries of the Third World, it is virtually impossible to establish living conditions that are somewhat dignified without allowing a massive growth in energy consumption.")

(3) Reducing the amount of energy wasted in the more developed countries and thus energy consumption. ("In the USA, the energy consumption per capita amounts to about twice that in Sweden, while the standard of living, however, is about the same in both countries...")

Strategies to buy time:

(4a) Switching to methanol as the main carrier of energy for the next century. The carbon dioxide problem would be cut in half because only half the energy produced by combustion of methanol originates from the oxidation of carbon; the other half comes from the oxidation of hydrogen. Methanol can be produced from coal through a well-tried process and could be used without requiring costly changes in the infrastructure. Fast breeders or huge solar energy installations could be used to provide the energy needed to produce this easy-to-use fuel. The breeders and the necessary reprocessing plants should be established under UN control on remote islands in the ocean.

(b) Dissolving carbon dioxide exhausted from conventional power plants in the deep ocean waters, which have a virtually unlimited capacity to dissolve this gas. Such installations would have to be sited at places where the ocean currents themselves could carry the dissolved gas into the deep layers (e.g., at the Strait of Gibralter). The costs of the project would not be prohibitively high.

(c) Reforestation--the most sensible way to mitigate atmospheric increases of carbon dioxide according to Breuer. A worldwide large-scale reforestation project would

- Be effective in reducing atmospheric carbon dioxide for at least several decades
- Bring about many ecological benefits, and even increase overall agricultural production (be reducing erosion, flooding, etc.)
- Have an economic impact that is relatively easy to assess
- Be technically feasible.

The main problem with approach 4c might be political feasibility. Would rich countries be willing to invest large sums of money in reforestation projects, whose benefits would only accrue after several decades? However, the political feasibility question must be dealt with in all strategies, except for the "wait-and-see" policy.

7. Breuer, G., "Can Forest Policy Contribute to Solving the Carbon Dioxide Problem," Environ.Int., 2: 499-451, 1979.

Worldwide, large-scale reforestation could provide, within 15-20 years, a biosphere sink of the order of magnitude of the present input from fossil fuel burning. Although the capacity of this carbon reservoir would be limited to a period of several decades, that time could be used to develop alternative energy sources (e.g., solar, geothermal) that are now unavailable for large-scale use. An increased carbon dioxide supply might slightly increase productivity on well-fertilized and well-watered agricultural land, but this would have no bearing on the atmosphere because most crops are reconverted to carbon dioxide within a short period. Forests would be a longer lasting reservoir. Breuer also notes that in tropical forests, secondary vegetation will not take up more than about 10-20% of the carbon stored originally in primeval forests.

8. Broecker, W.S., et al., "Fate of Fossil Carbon Dioxide and the Global Carbon Dioxide Budget," Science 206: 409-418, 1979.

This paper evaluates various global carbon budgets. About one-half of the carbon dioxide released from fossil fuels appears to remain airborne. Three possibilities exist for the other half: storage in the terrestrial biosphere (mainly as wood and soil humus); in the sea (mainly as dissolved inorganic carbon); or in shallow-water sediments (mainly as organic residues). The authors conclude that current estimates of ocean uptake are sufficiently firm (although entirely based on modeling efforts) to exclude the possibility that appreciably more excess carbon dioxide is dissolved in the sea than has been estimated. Consequently, they look to the biosphere (living and dead) to balance the carbon budget. They state that the regrowth of previously cut forests and the enhancement of forest growth resulting from the excess carbon dioxide in the atmosphere have probably roughly balanced the rate of forest destruction during the past few decades.

They adopt the following carbon budget of the fossil fuel carbon dioxide that has been generated between 1958 and the present:

Fraction	Fate
0.52 ±0.04	Remains airborne
0.37 ±0.04	Taken up by the sea
0.02	Forms organic residue when carbon atoms react with anthropogenic phosphorus atoms
0.09	Taken up by the biosphere.
1.00	

9. Chan, Y.-H, and J.S. Olson, Simulation of Land-Use Patterns Affecting the Global Carbon Cycle, Oak Ridge National Laboratory, Oak Ridge, Tenn. (Originally presented as the author's thesis, University of Tennessee, Knoxville), 173 pp., 1979.

See Abstracts # 10 and 11 below.

10. Chan, Y.-H, and J.S. Olson, "Limits on the Organic Storage of Carbon from Burning Fossil Fuels," J. Environ. Manage 11: 147-163, 1980.

Computer simulations of a global carbon model are used to determine the limits on the organic storage of carbon from the burning of fossil fuels and the clearing of tropical forests. It is assumed that increased atmospheric carbon dioxide would stimulate net primary production of terrestrial biota. However, possible storage would be reduced by physiological limiting factors. Under optimistic conditions, a 16% increase of carbon storage in the biosphere organic pools is projected as the plausible upper limit.

11. Chan, Y.-H., et al., "Land Use and Energy Scenarios Affecting the Global Carbon Cycle," Environ. Int. 4: 189-206, 1980.

A simulation model was used to reconstruct changes in the global carbon cycle since 1860 and to project four hypothetical future scenarios of carbon dioxide injection to 2460. The scenarios represent the combinations of two schedules of fossil fuel burning (early vs. late) with two hypothetical deforestation rates (high vs. low) in tropical forests.

The authors note that, to date, models of the total global carbon cycle have not included a sufficiently detailed representation of carbon circulation in terrestrial ecosystems. Thus testing hypotheses about the fluxes of carbon due to forest clearing has been impossible. To offset those deficiencies, their model includes 19 compartments and their exchanges of carbon, including slow and rapid exchange of carbon in tropical forests ("southern woods"), in other wooded ecosystems ("northern woods") and in unforested areas ("nonwoods"--lands converted from forests to agricultural land). The present model includes many slow fluxes and relatively inactive pools so that the total carbon in nature can be considered to cycle within a closed system. The land biosphere itself is considered both as a source and sink for atmospheric carbon dioxide. During the next 25 years, the forests may lose carbon to the atmosphere because of land clearing; at the same time the nonforest ecosystems, which are mainly agricultural lands, would increase their total area and serve as sinks for bigger amounts of the excess carbon dioxide. After 2050, the terrestrial biosphere could maintain a relatively constant mass of organic carbon if the carbon dioxide fertilization effect is moderate.

The scenarios indicate that the carbon from fossil-fuel combustion clearly is the major contributor to the atmospheric carbon. The authors conclude that the basic strategy in the long-term management of atmospheric carbon dioxide should consist of reducing fossil-fuel consumption, keeping part of the fossil carbon as a source of new synthetic materials for the generations to come. Drastic changes in biosphere management can be used as a supplementary policy during the transition period (possibly a century) in developing some other energy sources acceptable to society.

12. Chen, K., et al., "Carbon Dioxide from Fossil Fuels," Energy Policy, 8: 318-330, Dec. 1980.

This article discusses carbon dioxide control strategies and notes that no practicable means for controlling carbon dioxide have been demonstrated. Much of the problem is in the staggering amount of carbon dioxide generated, typically about 20 wt% of flue gas from coal-fired power plants. The effectiveness of carbon dioxide control depends on the timing and extent of its implementation, as well as the technical and economic feasibility of the control technologies.

Four classes of carbon dioxide strategies are discussed:

(1) Choice of Fuels or Energy Technology--Carbon released as carbon dioxide per 100 quads of end use energy as heat through direct combustion is about 0.725×10^9 tonnes for natural gas, 1×10^9 tonnes for oil, and 1.25×10^9 tonnes for coal. Considerable differences exist in the amount of carbon dioxide emitted and fossil fuel consumed by different energy technology systems when extraction, production distribution, reconversion, and end use are all included. For example, the carbon dioxide released from synthetic fuels is about 2.3 times greater than that released by natural gas for the same amount of electricity generation, and about 50% higher than the direct combustion of coal.

(2) Carbon Dioxide Capture--This strategy is questionable because of increased costs and efficiency losses. Fossil fuel power plant stacks are the most likely control point to install aqueous potassium carbonate scrubbing. However, this approach would reduce the net energy output of the plant from 37% to 30% and would perhaps double the capital costs of power plants. Cryogenic separation would use more energy for carbon dioxide capture than the plant produces.

(3) Carbon Dioxide Storage--The deep ocean has an enormous capacity. Terrestrial storage might take place in salt domes or through injection into oilfields for enhanced oil recovery; however, both of these options would afford small storage capacity.

(4) Carbon Dioxide Conversion--The costs for reforestation and general fertilization of existing forests; in terms of capital and redistribution of resources, make these strategies impracticable. An alternative biological approach is to convert flue gas carbon dioxide using on-site control technologies (e.g., by bacterial action that converts carbon dioxide to methane). Again, such conversion would be limited by capital and resource costs. Use of

> plant material as biomass for energy would only have a transient conversion effect. Another method for converting recovered carbon dioxide to synthetic liquid and gaseous carbonaceous fuels using nuclear reactors has been investigated, but the energy requirements clearly favor direct use of the nuclear capacity for energy production.

The authors conclude that carbon dioxide capture by scrubbing with disposal in the deep ocean is the most feasible control alternative available. Although perhaps impracticable from the standpoint of costs and efficiency losses, large centralized coastal facilities appear to be the most amenable to carbon dioxide control and disposal. Contingency plans should also include curtailment of fossil fuel use and application of carbon dioxide control technology.

Although no country can control carbon dioxide unilaterally, the United States accounts for more than a quarter of all fossil fuel carbon dioxide emissions, and possesses a quarter of the world's coal resources. It could assume a much needed leadership role in solving the carbon dioxide problem.

13. Crabs, L., et al., "Energy Savings for Carbon Dioxide Removal Systems," Paper delivered at AIChE, 72nd Annual Meeting, AIChE, New York, NY, November 25-29, 1979.

This paper evaluates the energy requirements for carbon dioxide removal systems by conducting an "exergy" balance analysis. According to the authors, the exergy of a system is a measure of maximum useful work that can be obtained in a reversible process operating between the parameters of the system and those of the environment. Four different flow-sheet configurations which use a potassium carbonate solution and one MEA flow-sheet are analyzed. The exergy supply (10^6 Btu/h) for these configurations is summarized below:

Process Flow Sheet	1 Isothermal	2 Carsol	3 Dual Pressure	4 Carsol	5 MEA
Exergy Supply to Systrem	62.175	57.585	48.730	46.913	61.088
Exergy Exported with CO_2	0.599	0.599	2.25	0.599	0.599

Process economies and design aspects are also discussed.

14. Dang, V.D., and M. Steinberg, "The Value of Forestation in Absorbing Carbon Dioxide Surrounding a Coal-Fired Power Plant," Brookhaven National Laboratory Report No. 51279, 22 pp., 1980.

Forestation is examined as a means for removing and controlling atmospheric carbon dioxide at a distance of 5 to 10 km away from the power plant stack. Using an equilibrium approach to carbon dioxide plume dispersion, the increase in concentration of carbon dioxide above background is expected to be less than 1 ppm, and thus the forest growth rate would not be affected.

A second dispersion process was considered in which carbon dioxide is removed instantaneously by the trees while taking advantage of a higher carbon dioxide concentration due to the plume dispersion at ground level. In this dynamic approach, removing equivalent amounts of carbon dioxide from the power plant by cultivating forests near the plant would result in 3-15% less area required for forestation, compared to remote planting. Therefore, it is suggested that sufficient increased regional forested areas be provided on a global scale to absorb the equivalent increase in carbon dioxide emission due to increased fossil fuel use.

15. Degens, E.T., "The History of Carbon Dioxide," Environ. Int. 2: 401-408, 1979.

This article discusses the environmental parameters that control the carbon dioxide system, past and present. On arrival on earth, the chemically reduced carbon pool split into various compartments: core, mantle, crust, hydrosphere, atmosphere, and biosphere. Mantle and crustal evolution is the dynamo recharging the carbon dioxide in sea and air. The present rate of carbon dioxide release from the magma is 0.05×10^{15} grams of carbon per year. Such rates are too small to seriously affect atmospheric carbon dioxide because of the enormous buffering capacity of the ocean. Geological field data and stable isotope work indicate that the carbon dioxide content in the atmosphere has remained fairly uniform since early Precambrian time. In contrast, the present man-made input of carbon dioxide into our atmosphere is so dramatic that serious environmental consequences are expected in the near future.

16. Delcourt, H.R., and W.F. Harris, "Carbon Budget of the Southeastern U.S. Biota: Analysis of Historical Change in Trend from Source to Sink," Science 210: 321-323 October 1980.

Using agricultural census statistics and forest survey records, the authors determined that from 1750 to 1950 the Southeastern United States was a net source for carbon at an average rate of 0.13 gigatons per year. Only in the past 20 to 30 years has increased productivity of commercial forests resulted in this region becoming a sink for atmospheric carbon dioxide. Forests in eastern North America today appear to be sinks rather than sources of atmospheric carbon dioxide. However, in the Southeast, only 0.07 Gigaton of carbon is being restored annually, or half the rate that was lost. This amounts to a recovery of only 3.1% of the carbon lost from 1750 to 1950. A 10% decrease in the area of commercial forest could change the Southeast from a carbon sink to a small source. Only with sustained high productivity, stabilization or increase in commercial forest area, and greater net growth can the terrestrial system of the Southeast continue to gain carbon. Managed reforestation can never completely offset the losses incurred by initial deforestation because of the differences in biomass between virgin and secondary forests. However, carbon loss resulting from the deforestation of an area could be offset by reforesting elsewhere.

17. Delcourt, H.R., and D.C. West, "Forests of the Southeastern United States: Quantitative Maps for Aboveground Woody Biomass, Carbon, and Dominance of Major Tree Taxa," Ecology 62: 879-887, 1981.

Summary maps depict the current distribution patterns of aboveground woody biomass and carbon content of the commercial forests in the southeastern United States, an area comprising 15% of the temperate forest zone of the earth. The maps show locations of present reservoirs (concentrated in areas of managed national forests), as well as areas where biomass and carbon pools can yet be increased through forestation.

In the Southeast today, secondary forests store 75% of the total carbon within the terrestrial biota. More than 20% is in cropland, but less than 5% remains in virgin forest. Major land use changes are anticipated in the Southeast in the next 10-20 years. Oldfield succession and reforestation of the Piedmont in Georgia and the Carolinas should result in a net increase of biomass and carbon in secondary forests of that region, whereas the southeastern bottomlands (e.g., back swamps within the Mississippi River Valley) are expected to be converted largely to cropland.

18. Dyson, F.J., and G. Marland, "Technical Fixes for the Climatic Effects of Carbon Dioxide," Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, March 7-11, 1977, Miami Beach, FL, W.P. Elliott and L,. Machta, eds. in Carbon Dioxide Effects Research and Assessment Program, CONF-770385, May 1979.

This paper presents order-of-magnitude estimates of the feasibility and size of emergency plans that might be proposed if the danger of atmospheric carbon dioxide accumulation becomes acute. The authors note that if the carbon dioxide withdrawal were to begin now

(1977) 2.5×10^9 metric tons of carbon per year would have to be removed. Assuming that by the year 2000 the rate of fossil fuel use is between 2 and 4 times the present rate, the required rate of carbon dioxide withdrawal between now and then will lie in the range of 2.5×10^9 to 1×10^9 tons of carbon per year. They take the value of 5×10^9 tons per year as illustrative of the magnitude of the problem that would arise if the withdrawal plan had to be implemented sometime within the next 25 years.

Following is a summary of the emergency plans they evaluated:

(1) Physical transfer of carbon dioxide to the deep ocean, including Marchetti's scheme for accelerating downward mixing of carbon into the deep ocean (see Abstract Numbers 32 and 33 below). Dyson and Marland do not speculate whether this scheme is environmentally acceptable or even technically feasible. They point out, however, that the current emission of fossil fuel carbon is already approximately twice the carbon flux in the Mediterranean outflow water. The authors also believe that Marchetti may have underestimated the cost to the consumer involved with the energy demands of this system. In fact, almost all of the power plant out might be required for carbon dioxide processing.

(2) Transfer of carbon dioxide to the long-term biosphere. As a short-term response while a shift to nonfossil fuels was implemented, it might be possible to plant enough trees and other fast-growing plants to incorporate the excess carbon dioxide and retard the annual atmospheric increase. This could be done by growing long-lived trees that are left unharvested or by growing short-lived plants that are converted to humus or allowed to acccumulate in artificial peat bogs. Either method requires large areas of land and any plan for forced, rapid growth of plants will require the use of fertilizers. The total area of forest in the world is about 5×10^7 km^2. To absorb 5×10^9 tons of carbon per year from the atmosphere, it would be necessary to achieve an average worldwide increase in long-term forest growth of 100 tons of carbon per km^2 per year, or a growth of 750 tons per km^2 per year on one-seventh of the earth's forested area. The United States could potentially provide about one-tenth of the required growth of trees.

If plants such as water hyacinth are intensively cultivated and stored in a semipermanent fashion, an area of 8×10^5 km^2 would be needed. The total area of tropical swampland that might, with some adaptation, be suitable for water hyacinths is about 25×10^5 km^2, more than 90% of which is outside the United States. It remains uncertain as to whether the artificial peat bogs required to store the plant material are either feasible or environmentally acceptable.

The availability of fertilizer will probably be the critical factor limiting the scale and speed of carbon fixation. For example, implementing the forestation scheme described above might require 40% of the world production of nitrogen and K_2O, and 20% of the P_2O_5 in fertilizers produced in 1974.

(3) Biological transfer of carbon dioxide to the deep ocean--through downward transport of carbon as biologically treated detritus (a concept presented in a draft paper by Broecker) surface waters are supplied with the biological limiting nutrient (phosphate and/or nitrate). Thus the growth of organisms is accelerated. The fertilizer requirement for incorporating 5×10^8 tons of carbon per year might come to 7.2×10^8 tons of nitrogen and 1.1×10^8 tons of phosphorus. Production of these amounts of fertilizer would consume about three-fourths of current U.S. energy consumption. However, if oceans can select for nitrogen-fixing algae, only phosphorus might have to be supplied. Nonetheless, the phosphorus required still amounts to 10 times the 1974 world production rate of phosphate fertilizers.

(4) Other Technical Fixes

  (a) Using nuclear-generated electricity to extract carbon dioxide from the atmosphere and converting it into a liquid hydrocarbon (methanol). Although technically feasible, to remove 5×10^9 tons of carbon per year would require 5700 plants of 1,000 MW each of dedicated nuclear capacity operating at 80% capacity factor.

  (b) Balancing the carbon dioxide-induced heat retention with artificial alteration of the earth's albedo.

The authors conclude that although all of these possibilities are massive in scale, the biologically based scenarios seem to have the greatest possibility for implementation.

19. Gessel, S.P. and P. Zinke, "Significance to Forestry of the Dahlem Conference on Global Chemical Cycles and their Alteration by Man," Forestry, 76: 48-59, January 1978.

The role of forests in carbon supply (source or sink) seems to depend on management practices. Practices and factors that are causing forest lands to be a source of carbon dioxide include:

- Extensive use of forests for industrial raw materials
- Uncontrolled fires burning large areas
- Removal of and change in forest cover, resulting in accelerated release of carbon dioxide from the soil
- Extensive use of wood for fuel
- Management in very short rotations
- More complete use, leaving less material stored on site.

20. Gifford, R.M., "Carbon Dioxide and Plant Growth Under Water and Light Stress: Implications for Balancing the Global Carbon Budget," Search 10: 316, 1979.

To accommodate upward revisions of the magnitude of carbon dioxide emissions due to deforestation, the remaining intact biosphere may be serving as more of a sink that is commonly assumed.

21. Goudriaan, J., and G.L. Ajtay, "Possible Effects of Increased Carbon Dioxide on Photosynthesis," pp. 237-249 in Global Carbon Cycle: Scope 13, B. Bolin et al., (eds.) John Wiley and Sons, New York, NY 1979.

Plant production is limited more by shortages in water and nutrients than by atmospheric carbon dioxide, except under optimal plant growth conditions, like those achieved in greenhouses. However, carbon dioxide enrichment can directly increase plant production by an improved water use efficiency.

22. Hampicke, U., "Sources and Sinks of Carbon Dioxide in Terrestrial Ecosystems: Is the Land's Carbon Budget Balanced under the Influence of Man?" Environ. Int. 2: 301-315, 1979.

This paper evaluates the hypothesis that ocean-atmosphere models of carbon transfers are correct, and that major net losses of carbon in some terrestrial ecosystems are compensated for by equal gains in others. A balanced carbon budget can be achieved by combining low estimates for the terrestrial biota's carbon losses with high estimates for the gains. The extent and preciseness of existing available quantifiable data do not permit us to prove or disprove any one hypothesis about the carbon budget.

The other hypotheses noted are:

- Ocean-atmosphere models are correct, and there is no significant net loss of carbon in any major terrestrial biome

- The terrestrial biota is a net source, and ocean-atmosphere models are incorrect; ocean uptake is larger than the amount calculated by these models

- Ocean-atmosphere models are correct, and the terrestrial biota is a net source. Its losses of carbon are absorbed by an unidentified sink other than bicarbonate and carbonate ions in ocean water. Potential sinks might include dissolved organic matter in the ocean and the dissolution of carbonate sediments in shallow waters.

A knowledge of the global carbon cycle is important for the design of future energy strategies.

23. Kellogg, W.W., and R. Schware, Climate Change and Society, Westview Press, Boulder, Colorado, 1981.

This study Climate Change and Society includes a discussion on measures to avert carbon dioxide-induced climatic changes. The following categories or measures are covered:

(1) Reducing Fossil Fuel Demand--Conserve Energy. A Harvard University study by Stobaugh and Yergin concludes that U.S. conservation measures could result in 30-40% reductions in energy consumption. Virtually no reduction in the American standard of living would occur if

  - "Soft energy paths" (e.g., renewable energy sources such as solar and wind) were followed, or

  - "Hard energy paths" (e.g., fission and fusion) were followed.

(2) Employing Technical Solutions

  - Controlling carbon dioxide at the source is the most economical solution, although one still fraught with technical and financial problems. The authors cite Marchetti's ocean storage solution (see Abstracts 33 and 34 below), but they note that oceanic and atmospheric concentrations eventually come into equilibrium. They also point out that ocean currents are not always constant and predictable.

  - Employing other technical methods; for example, processing the separated carbon dioxide to produce carbon fuels--a scheme that requires exceedingly large amounts of energy

(3) Increasing Biomass, including Reforestation by expanding the natural sinks that absorb carbon dioxide. The authors cite the study by Cooper (1978) that points out that an increase of just 1% in the plant life on earth, especially the forests, would be sufficient to absorb one year's release of carbon dioxide at the present rate. The authors note, however, that sufficient resources (such as land, water, nutrients, manpower and capital) must be available and that disposal methods must be found to sequester fixed carbon for long periods.

Kellogg and Schware also identify specific strategies other than directly reducing carbon dioxide emissions to mitigate the effects of increased atmospheric carbon dioxide. These strategies include increasing the earth's resilience to climatic changes (e.g., protecting arable soil and impoving water management policies) and implementing programs that lead to improved choices (e.g., employing environmental monitoring systems and the transfer of appropriate technology).

24. Kohlmaier, G.H., "The Carbon Cycle: Sources and Sinks of Atmospheric Carbon Dioxide," Experientia 36: 769-776, 1980.

A synopsis of the major processes within the global carbon cycle is given. Atmospheric carbon dioxide content is now increasing by about 2.8 gigatons of carbon per year (about 1.55 ppm per year). Sources are considered to be as follows:

	Gigatons per Year of Carbon
Fossil fuel consumption	5
Reduction of phythomass	-0.5 -- 18 (center of estimates: 2.3)
Release of soil carbon	0.1--7.0

With oceans serving as a sink for 2.2 gigatons of carbon per year, and assuming the lower estimates of the carbon sources are correct, a source sink problem does not exist. However, when the upper values for biogenic and soil carbon release are considered a real source sink problem is noted. Recent evidence indicates that the effect of biogenic carbon on the atmosphere is less than originally considered because of incomplete combustion during phytomass burning, and that the uptake of carbon by the oceans is greater than originally thought because of river discharge of soil carbon from eroded areas into the ocean or by the downwelling of polar surface waters or an additional dissolution of Ca (CO_3).

25. Laurmann, J.A., "Fossil Fuel Utilization Policy Assessment and Carbon Dioxide Induced Climatic Change," pp. 253-261 in Carbon Dioxide, Climate, and Society, J. Williams, ed., Pergamon Press, Oxford, England, 1978.

This paper summarizes the scientific uncertainties associated with the consequences of increased fossil fuel use and discusses presents energy implications and recommendations based on this analysis. Available data suggest the need for immediate remedial measures in the form of global reduction of fossil fuel use. However, uncertainties confuse the issue with respect to the rate carbon dioxide atmospheric increases will occur. Laurmann suggests that probabilistic techniques employed in decision analysis might be useful in dealing with the uncertainties involved.

26. Laurmann, J.A., "Market Penetration Characteristics for Energy Production and Atmospheric Carbon Dioxide Growth," Science 205: 896-898, 1979.

Estimates are presented for the maximum rate at which fossil fuel consumption can be reduced according to the market penetration time concept by the introduction of noncarbon energy sources. The coincidence of the market penetration time (at least 50 years) with the date projected for hazardous carbon dioxide-induced climatic change (50-60 years, although with a large probable error) suggests that immediate action be taken. Laurmann questions, however, the applicability of market penetration ideas to energy consumption.

27. Laurmann, J.A., "Assessing the Importance of Carbon Dioxide-Induced Climatic Changes Using Risk-Benefit Analysis," pp. 437-460 in Interactions of Energy and Climate, W. Bach et al. (eds.), D. Reidel Publishing Co., Dordrecht, The Netherlands, 1980a.

Laurmann describes a decision analysis approach for estimating the economic impact of carbon dioxide induced climatic change. Of interest to the carbon dioxide control question is his conclusion that a cost/benefit analysis weighing the attractiveness of alternative carbon dioxide control strategies should be sensitive to the nature and magnitude of social discounting of future events. The paper suggests that the marginal benefit of any optimum control strategy in socially discounted dollar would not be large compared with natural climate variability costs. Unless market penetration times for new energy sources are as long as have been suggested, it is difficult to make a clear case for acting today to alleviate the potential carbon dioxide problem. Resolution of the market penetration time question is seen as central to the issue of the immediacy of the need for a carbon dioxide control policy.

28. Laurmann, J.A., "Climate Change from Fossil Fuel Generated Carbon Dioxide and Energy Policy," Environ. Int. 2: 461-474, 1980b.

The environmental impact of increasing carbon dioxide levels may be depicted as one of high risk and high uncertainty, with the critical period occurring some 50 years from the present, but with a significant probability of a much earlier impact. Because carbon cycles behave nearly linearly in this time range, projections of atmospheric carbon dioxide concentrations do not depend on detailed understanding of carbon cycle mechanisms.

Uncertainties associated with carbon dioxide atmospheric increases can be considerably narrowed only by considering the most immediate time frame of the impact. The remaining sources of uncertainty relate to

- Future anthropogenic release of carbon dioxide, both from fossil fuel use and, with larger uncertainty, from deforestation
- Global and regional climatic response to increased atmospheric carbon dioxide levels.

29. Lieth, H., "The Role of Vegetation in the Carbon Dioxide Content of the Atmosphere," Journal of Geophysical Research 68: 3887-3898, 1963.

The carbon dioxide exchange between the atmosphere and the biosphere takes place rapidly. Total carbon dioxide in the atmosphere above 1 hectare of an European forest could be exchanged in about 2 years and in the tropical zone in about 3/4 year. The total production capacity of the world vegetation could fix the entire carbon dioxide of the atmosphere in 23 to 26 years. In mature, natural vegetation an equilibrium exists between loss and gain of organic matter.

30 Lister, R., and E. Lemon, "Interactions of Atmospheric Carbon Dioxide, Diffuse Light, Plant Productivity and Climate Processes--Model Predictions," pp. 112-135 in ERDA Symposium Series

38, Atmosphere-Surface Exchange of Particulate and Gaseous Pollutants, R.J. Engelmann and G.A. Sehmel (eds.), CONF 740921, 1976.

Increasing carbon dioxide (and proportions of diffuse light) enhance photosynthesis of plant communities up to a point. Net photosynthesis (primary productivity) increases more in sugar beets (a C_3 carbon pathway crop) than in maize (a C_4 carbon pathway crop) with increasing atmospheric carbon dioxide levels. The authors speculate that terrestrial plants play a small role in dampening long-term atmospheric carbon dioxide perturbations.

31. Loomis, R.S., "Carbon Dioxide and the Biosphere," Global Effects of Carbon Dioxide from Fossil Fuels, W.P. Elliott and L. Machta (eds.), Proc. Workshop, Miami Beach, FL, March 7-11, 1977. DOE, CONF-770385, May 1979.

Although broad generalizations can be made, we now lack the information base necessary to carefully assess the biosphere's response to changes in atmospheric carbon dioxide concentrations. Soils are shown as potentially the most significant source/sink in the biosphere.

32. MacDonald, G., et al., The Long Term Impacts of Increasing Atmospheric Carbon Dioxide Levels, prepared by SRI International, Menlo Park, California as a JASON Technical Report, JSR-79-04 for the U.S. Department of Energy, Washington, D.C., June 1980.

A section of the report discusses possible means of dealing with the rate of increase of atmospheric carbon dioxide. Energy conservation appears to be the most effective near-term method of controlling carbon dioxide, however, alternative fuel sources could become significant within 50 years. The authors comment on several other ways of controlling carbon dioxide:

- In principle, carbon dioxide can be removed from stack gas effluent and then disposed by land (e.g., old petroleum fields) or sea burial. Preliminary estimates indicate that 5-10 billion gallons of oil would eventually be produced by enhanced oil recovery by carbon dioxide flooding. About one-half of a year of United States generation of carbon dioxide could be disposed of in a massive enhanced oil recovery scheme. However, stack gas effluent has relatively low concentrations of carbon dioxide, and high volume of gases are emitted by power plants and industrial facilities. The chemically reactive systems are the only economically feasible removal processes (e.g., MEA process) and these are still quite expensive. Additional costs would be involved in purifying the carbon dioxide, transporting it, and injecting it into gas or oil fields. These capital costs could raise the total costs well above $\$1/10^3 ft^3$. On the West Coast, where the continental shelf drops off sharply, ocean disposal would be less costly than land disposal. A mixed strategy of land and ocean disposal could be used to minimize the cost of physical removal of carbon dioxide. Such disposal would approximately double the cost of electricity generated by the use of carbon-based fuels, and measures would control only half of the carbon dioxide generated in the United States. About one-half of the carbon dioxide emissions in this country are from distributive sources from transportation (31%) and the residential, as opposed to utility electrical generation (29%) and the industrial sector (20%).

- An alternative disposal mechanism is to transfer carbon dioxide into a biospheric bank of carbon (e.g., by growing long-lived trees). The principal limitation to this scheme is land availability. A massive forestation program involving 16% of the earth's surface could ameliorate carbon dioxide effects. However, many institutional, political, social, and economic deterrents to massive forestation would be encountered. In addition, a principal technical limitation for rapid forced growth of trees would be the availability of fertilizer.

33. Marchetti, C., "On Geoengineering and the Carbon Dioxide Problem," Climate Change 1: 59-68, 1977.

Marchetti proposes a carbon dioxide control scheme in which carbon dioxide is partially or totally collected at certain transformation points and disposed of by injection into suitable sinking thermohaline currents that carry and spread it into the deep ocean. The Mediterranean undercurrent entering the Atlantic at Gibraltar has been identified as one such current; it would have sufficient capacity to deal with all carbon dioxide produced in Europe even in the year 2100. Marchetti rougly estimates a cost to the consumer of 10% of the fuel cost for a recovery of 50% of the carbon dioxide and 20% of the fuel costs for a recovery of 90%.

34. Marchetti, C., "Measures of Carbon Dioxide Control," Experientia 36: 767-890, 1980.

Rather than putting a tax on carbon dioxide emissions to keep emission levels under a set value, Marchetti proposes to dispose of the carbon dioxide. He makes three observations:

- o Plants circulate in their system about 10% of the carbon dioxide in the atmosphere every year.

- o Carbon dioxide ejected into the atmosphere stays there for a while because of kinetics, not because of poor sinks

- o Various kinds of geologic traps that were able to keep oil and gas in store for millions of years would probably be able to store carbon dioxide for the same amount of time.

The proposal to plant trees has two weak points: an astronomical number of trees would have to be planted and reforesting would change the local albedo and consequently the amount of energy absorbed from the incoming solar light--possibly moving us in the very direction of warming the earth that we are trying to avoid.

Two ocean sink scenarios are discussed. Revelle and Shapero suggested putting phosphorus (the typical limiting nutrient) into the ocean superficial waters. Plant productivity would increase and the amount of litter falling into the deep ocean, and thereby transporting unwanted carbon, would likewise increase. The amount of phosphorous to be injected would be perhaps 100 mt/y (not small, but a feasible amount).

Marchetti again proposes his scheme of using thermohaline currents in their sinking mode to operate deep injection. With respect to initially removing the carbon dioxide, the author notes that although ordinarily one has the scrubber after the construction chamber, one could have an air separator in front of the combustion chamber. Using pure oxygen (at high pressure) as an oxidant has many advantages; power plants would become very small, silent, and would produce no emissions.

For several reasons, it seems unsuitable to allow decisions regarding carbon dioxide control to wait until a possible carbon dioxide effect is observed. Shift to nonfossil energy technology would take several decades, and the atmospheric carbon dioxide level would decrease only very slowly after cessation of carbon dioxide production.

35. Moore, P.D., "Atmospheric Carbon Dioxide and Forest Clearance," Nature 268: 296-297, July 1977.

The use of fast-growing forest species as a carbon sink is evaluated. Although forests represent a major carbon reservoir, not all are efficient carbon sinks. Most natural forest vegetation is at or near a climax or equilibrium state. The loss in carbon dioxide consumption resulting from replacement of low-grade forest, as well as the energy expenditures necessary for the establishment, management, fertilization, harvest, and storage of such crops, must also be considered.

36. Mustacchi, C., et al., "Carbon Dioxide Disposal in the Ocean," pp. 283-289 in Carbon Dioxide, Climate and Society, J. Williams (ed.), Pergamon Press, New York, NY, 1978.

Disposal of carbon dioxide from power station flue gas involves

- Finding a system that can receive the amounts of carbon dioxide in question without major alterations
- Choosing a suitable strategy and the relevant technology to transfer the carbon dioxide from the source to the acceptor system.

Photosynthetic fixation of carbon dioxide is only a theoretical system unless a closed circuit is established. Even then, 100 m^2 of forest per kw would be required. One could also forego complete oxidation of fossil fuels and stop at alcohols, aldehydes, etc., as combustion products. However, one would only obtain about one half the Kcal/kg of hydrocarbon in this scheme.

The ultimate sink appears to be the ocean. The following three alternative ways carbon dioxide can be disposed in the ocean are discussed including their relative costs:

Carbon Dioxide Disposal Plan	Investment ($/kWe)	Operation and Depreciation ($/kWh)
Whole flue gas bubbling	130	0.03
Amine absorption	70	0.8
Seawater absorption	110	0.8

The authors conclude that in removing the carbon dioxide no major difficulty and only moderate costs would be involved. The preferred processes are those involving separation of carbon dioxide by absorption stripping in the plant. By optimizing the process detail, the additional cost per kWh electric is expected to be not higher than 20%, and probably lower.

37. Mutacchi, C., et al., "Carbon Dioxide Removal from Power Plant Exhausts," Environ. Int. 2: 453-6, 1979.

This report is similar to Abstract 36 but has more engineering detail. Various options for removing carbon dioxide from power plant exhaust gases are reviewed. The authors conclude that the disposal of carbon dioxide in the ocean is a feasible operation making use of available technologies, even though the scale of use is of an unusual magnitude. Three types of carbon dioxide disposal plants are evaluated, including depreciation and operating costs:

Carbon Dioxide Disposal Plant	Investment ($ x 10^6)	Operation and Depreciation (¢/kWh)
Whole flue gas bubbling	144	1.1
Amine absorption	84	0.27
Seawater	206	0.62

The additional cost of electricity due to carbon dioxide disposal by these means is not expected to exceed 15%.

38. Patton, J.T., "Enhanced Oil Recovery by Carbon Dioxide Flooding," Energy Communications 4:1, 1978.

Carbon dioxide flooding possesses a unique ability to displace crude oil from reservoir rock and can profitably recover additional oil, at world oil prices, from depleted fields. Economic studies indicate that the carbon dioxide price cannot exceed about 25% of that for oil if a project is to be commercial. With oil selling at $12/b, $480/ton, this means that carbon dioxide delivered to the well site in the neighborhood of $20/ton would be required for profitable operation. The application of carbon dioxide flooding should become commercially significant around 1980.

39. Roether, W., "The Effect of the Ocean on the Global Carbon Cycle," Experientia 36: 1017-1025, 1980.

The fate of fossil fuel carbon dioxide in the ocean is discussed and a comparison made with the natural oceanic cycle of carbon. The oceanic share of fossil fuel carbon, now about 40%, will decrease to about 20%. Much of the fossil fuel carbon will remain in the atmosphere. The oceanic uptake of carbon dioxide from the atmosphere will then be so slow that the atmospheric carbon dioxide partial pressure will stay high for several centuries, even after fossil-fuel burning has virtually ceased. The maximum carbon dioxide partial pressure will therefore primarily depend on the total of fossil fuel burned and much less so on the rates of burning. The atmospheric carbon dioxide will constitute an environmental burden for many generations to come.

40. Rotty, R.M., "The Atmospheric Carbon Dioxide Consequences of Heavy Dependence on Coal," pp. 263-273 in Carbon Dioxide, Climate and Society, J. Williams (ed.), Pergamon Press, New York, NY, 1978.

Rotty's paper includes two scenarios indicating global carbon dioxide production percentages by world segments:

Country	1974 Scenario	2025 Scenario
United States and Canada	29	9
Western Europe	18	8
USSR and Centrally Planned Europe	25	31
Developing Countries	13	33
Centrally Planned Asia	8	16
Japan, Australia, and New Zealand	7	3
	100	100

Rotty emphasizes that controlling the rate of fossil fuel use while maintaining hope for increased standard of living for in the impoverished of the world will require extremely careful planning and the ability to deploy so-called inexhaustible energy sources effectively.

41. Rotty, R.M., "Present and Future Production of Carbon Dioxide from Fossil Fuels--A Global Appraisal." Workshop on the Global Effects of Carbon Dioxide from Fossil Fuels, March 7-11, 1977, Miami Beach, FL, W.P. Elliott and L. Machta (eds.) in Carbon Dioxide Effects Research and Assessment Program, CONF-770385, May 1979.

This article is similar to Abstract Number 40. Rotty emphasizes that the level of carbon dioxide in the atmosphere is a problem of worldwide proportions. Unilateral action by any one nation in planning alternatives to fossil fuel use will most likely be ineffective in controlling carbon dioxide.

42. Rotty, R.M., "Past and Future Emission of Carbon Dioxide," Experientia 36: 781-783, 1980.

Similar to Abstracts 40 and 41, Rotty stresses the global viewpoint that is necessary for developing plausible energy scenarios and associated carbon dioxide emission properties. Rotty also notes that there is little doubt that some portions of the terrestrial biota serve as a major source of carbon dioxide (as a result of the destruction of tropical forests), whereas others serve as sinks--at least for several decades. Obtaining reliable information on either clearing or regrowth on a global scale is extremely difficult, if not impossible.

43. Schneider, S.H., "Climatic Limits to Growth: How Soon? How Serious? " pp. 219-225 in Carbon Dioxide, Climate, and Society, J. Williams (ed.), Pergamon Press, New York, NY, 1978.

Schneider suggests steps that can be taken to minimize society's vulnerability to carbon dioxide atmospheric buildup and resulting climatic changes:

- Learn the range of possibilities so that facts and values can be more easily distinguished
- Focus current energy debate on growth rate issues, particularly for third world countries
- Conserve energy and develop alternative solar or other renewable resources
- Begin now to minimize our economic dependence on energy growth.

Policymakers should realize that judgments will have to be made about how to weigh risks and benefits in the face of large uncertainties. Although scientists in many cases cannot definitely assess the risk/benefit issues, they can narrow the range of possibilities. But in the case of carbon dioxide, we cannot wait for research to turn up more technical certainty; we need political decisions today.

44. Sisson, W., "Nomogram Determines Carbon Dioxide Values for Fuels," Power Eng. 83:69, 1979.

Because carbon-hydrogen ratios of different fuels vary considerably, the maximum percentage of carbon dioxide in the flue gas also varies over a wide range. Approximate maximum carbon dioxide values for complete combustion of various fuels are shown on a nomogram.

45. Sleeper, D., "Fuel Combustion Adds to Anxiety over Carbon Dioxide Buildup," Cons. Found. Lett., August 1979.

We now have the capability of changing the climate of the entire planet. Most scientists agree that atmospheric carbon dioxide buildup is warming the climate. Many pitfalls remain to a speedy resolution of the problem; (1) scientific uncertainty, particularly about the global carbon budget; (2) energy crunch; (3) international cooperation, (4) public apathy. Various strategies are discussed for controlling atmospheric carbon dioxide, from changing energy mixes to technological fixes. The author concludes that societies have proven marvelously ill-equipped to deal with crises that lurk just around the corner.

46. Speth, G., "Global Energy Futures and the Carbon Dioxide Problem, Boston Coll. Environ. Aff. Law Review, 9: 1-11, 1980.

Three recommendations for dealing with the carbon dioxide problem are given:

- Assign a high priority to incorporating the carbon dioxide issue in U.S. energy planning
- Increase reliance on energy conservation and renewable sources of energy
- Undertake new and expanded cooperative international efforts to address carbon dioxide issues.

47. Steinberg, M., "Technologies for the Recovery and Disposal of Carbon Dioxide," paper delivered at National American Chemical Society Summer Meeting, New York, NY, August 23, 1981, BNL Project 29526, 1981.

The technical feasibility and economic costs of carbon dioxide control were evaluated. Four ways of disposing the captured carbon dioxide are considered: injection in the deep ocean; terrestrial burial; storage in plants and trees; and conversion of carbon dioxide to useful products. Even though the costs would be substantial, deep ocean disposal appears to be a possibility.

48. Steinberg, M., A.S. Albanese, and V. Dang, "Environmental Control Technology for Carbon Dioxide," AIChE Symposium Series 76: 154-171, 1980.

This paper is similar to Abstract Number 1. Steinberg *et al.* present a systematic overview of a number of routes for removal, recovery, disposal, and reuse of carbon dioxide from various control points in the global system. Criteria for evaluation are the energy and mass balances for the various routes. The following recommendations are made:

- o Attempt to find and use more natural gas (and petroleum) in place of coal which has higher carbon dioxide emissions per unit of energy produced
- o Consider recovering the more concentrated carbon dioxide industrial stack gas emissions by increasing the fossil fuel power used at the plant to supply the energy necessary
- o Attempt to recover the less concentrated atmospheric and oceanic carbon dioxide by using nonfossil power
- o Consider deep ocean disposal of carbon dioxide
- o Combine coal with nuclear electrolytic hydrogen to produce SNG
- o Produce synthetic carbonaceous fuel from atmospheric carbon dioxide and nuclear electrolytic hydrogen to produce SNG
- o Convert to a hydrogen economy using a nonfossil energy source
- o Convert to an all electrical economy using a non-fossil fuel source
- o Convert to biomass-photosynthetic energy economy.

49. U.S. Bureau of Land Management, "Carbon Dioxide Project, Wasson Field/Denver Unit, Draft Environmental Impact Statement," DES-79-37, Information Resource Press, 2100 M St, N.W., Washington, DC, 1979.

This draft environmental impact statement analyzes the consequences of the construction of 140 wells, 13 central facilities within the well field, and a 478-mile pipeline to transport carbon dioxide from southeast Colorado through New Mexico to the Wasson Oil Field near Denver City, Texas. The carbon dioxide wells would remove approximately 400 million ft^3/d of carbon dioxide. As many as 280 million b of oil could be recovered by the project. The report describes the magnitude and type of the ecological habitats that would be disturbed and the degree the visual air quality would be impaired.

50. Williams. J., "The Effects of Different Energy Strategies on the Atmospheric Carbon Dioxide Concentration and Climate," pp. 239-248 in Carbon Dioxide, Climate, and Society, J. Williams (ed.), Pergamon Press, New York, NY, 1978.

Assessing the implications of future atmospheric carbon dioxide concentrations requires 3 models:

- An energy model to estimate the future use of fossil fuels, and thus to estimate the impact of fossil fuel carbon dioxide into the atmosphere
- A carbon cycle model, that considers the reservoirs of carbon and the transfers between them for use in estimating the amount of carbon dioxide that will remain in the atmosphere
- A climate model to estimate the effects of atmospheric carbon dioxide on the climate.

Various energy strategy scenarios are discussed. The strategy that results in the smallest climatic effect shows a peak in carbon dioxide emissions in 2000 and a rapid decline thereafter, whereas the strategy resulting in the largest climatic effect shows continually increasing carbon dioxide emissions.

Appendix C

EXAMPLES OF RESEARCH BEING CONDUCTED AT U.S. UNIVERSITIES RELATING TO CARBON DIOXIDE EFFECTS ON PLANTS

University	Research Area	Principal Investigators
Kansas State University Manhattan, Kansas	Determining the effect of exhaust air from an animal shelter on greenhouse production	C. K. Spillman
Kansas State University Manhattan, Kansas	Optimizing water use of agronomic crops as related to responses to enhanced carbon dioxide levels	E. T. Kanemasu
Michigan State University East Lansing, Michigan	Investigating the physiology of carbon balance in deciduous trees	J. A. Flore
Michigan State University East Lansing, Michingan	Accelerating tree growth through breeding and intensive culture, maximizing the potential of enhanced carbon dioxide levels	J. W. Hanover
Mississippi State College State College, Mississippi	Determining direct effects of enhanced carbon dioxide levels on field crops in field growth chambers; developing a predictive model	D. N. Baker
Purdue University Lafayette, Indiana	Identifying carbon assimilation, partitioning, and transport in the soybean leaf	H. R. Koller
Rutgers, The State University of New Jersey New Brunswick, New Jersey	Investigating life histories and ecological requirements of aquatic weeds as related to carbon dioxide uptake	D. N. Riemer

University	Research Area	Principal Investigators
Texas A&M College Station, Texas	Determining the physiological role of dark respiration in the carbon economy of crop plants	K. J. McCree
University of Arkansas Fayetteville, Arkansas	Improving post-harvest handling of horticultural crops including carbon dioxide treatments	R. W. Buescher
University of Florida Gainesville, Florida	Determining direct effects of enhanced carbon dioxide levels on field crops in field growth chambers; developing a predictive model	L. H. Allen
University of Michigan Ann Arbor, Michigan	Conducting basic research on the physiological ecology of photosynthesis in crop plants	D. M. Gates
University of North Carolina Raleigh, North Carolina	Determining direct effects of enhanced carbon dioxide levels on field crops in field growth chambers; developing a predictive model	W. W. Heck H. H. Rogers T. R. Sinclair
University of Tennessee Knoxville, Tennessee	Determining the effect on crop yields of major environmental fluxes, including carbon dioxide levels	W. L. Parks
University of Wyoming Laramie, Wyoming	Developing physiological criteria for forage plant breeding including response to carbon dioxide levels	R. H. Delaney
Washington State University Pullman, Washington	Investigating photosynthetic carbon metabolism and water-use efficiency in C3 and C4 plants	R. A. Kennedy

APPENDIX D

CURRENT INVESTIGATORS OF THE DIRECT BIOLOGICAL EFFECTS OF ENHANCED CARBON DIOXIDE LEVELS

This appendix lists the names and addresses of a few of the principal scientists investigating the terrestrial (largely botanical), aquatic, and human health effects of enhanced atmospheric carbon dioxide levels. For a more complete listing, see AAAS (1980), pp. 71-76.

I. Terrestrial Ecosystems

Dr. L.H. Allen, Jr.
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Dr. Edward T. Kanemasu
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